DECAY OF TAILS AT EQUILIBRIUM FOR FIFO JOIN THE SHORTEST QUEUE NETWORKS

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In join the shortest queue networks, incoming jobs are assigned to the shortest queue from among a randomly chosen subset of $D$ queues, in a system of $N$ queues; after completion of service at its queue, a job leaves the network. We also assume that jobs arrive into the system according to a rate-$\alpha N$ Poisson process, $\alpha < 1$, with rate-1 service at each queue. When the service at queues is exponentially distributed, it was shown in Vvedenskaya et al. [16] that the tail of the equilibrium queue size decays doubly exponentially in the limit as $N \to \infty$. This is a substantial improvement over the case $D = 1$, where the queue size decays exponentially.

The reasoning in [16] does not easily generalize to jobs with non-exponential service time distributions. A modularized program for treating general service time distributions was introduced in Bramson et al. [4]. The program relies on an ansatz that asserts, in equilibrium, any fixed number of queues become independent of one another as $N \to \infty$. This ansatz was demonstrated in several settings in Bramson et al. [5], including for networks where the service discipline is FIFO and the service time distribution has a decreasing hazard rate.

In this article, we investigate the limiting behavior, as $N \to \infty$, of the equilibrium at a queue when the service discipline is FIFO and the service time distribution has a power law with a given exponent $-\beta$, for $\beta > 1$. We show under the above ansatz that, as $N \to \infty$, the tail of the equilibrium queue size exhibits a wide range of behavior depending on the relationship between $\beta$ and $D$. In particular, if $\beta > D/(D-1)$, the tail is doubly exponential and, if $\beta < D/(D-1)$, the tail has a power law. When $\beta = D/(D-1)$, the tail is exponentially distributed.

1. Introduction. We consider join the shortest queue (JSQ) networks, where incoming “jobs” (or “customers”) are assigned to the shortest queue from among $D$ distinct queues, $D \geq 2$, with these queues being chosen

*Supported in part by NSF Grant CCF-0729537
†Supported in part by NSF Grant CCF-0729537 and by a grant from the Clean Slate Program at Stanford University

AMS 2000 subject classifications: 60K25, 68M20, 90B15
Keywords and phrases: Join the shortest queue, FIFO, decay of tails.
uniformly from among the $N$ queues in the system, with $D \leq N$. When two or more of these queues each have the fewest number of jobs, each of the queues is chosen with equal probability. After completion of service at its queue, a job leaves the network. We assume that jobs arrive according to a rate-$\alpha N$ Poisson process, $\alpha < 1$, and that jobs are served independently and at rate 1 at each queue. We are interested in this article in the case where the service discipline at each queue is first-in, first-out (FIFO).

When the service at queues is exponentially distributed, the evolution of the system is given by a countable state Markov chain where a state is given by the number of jobs at each queue. It is not difficult to show that a unique equilibrium distribution exists; this equilibrium is exchangeable with respect to the ordering of the queues. Let $P_k^{(N)}$ denote the probability that there are at least $k$ jobs in equilibrium for the system with $N$ queues. It was shown in Vvedenskaya et al. [16] that

$$\lim_{N \to \infty} P_k^{(N)} = \frac{\alpha (D^k - 1)}{(D - 1)} \quad \text{for } k \in \mathbb{Z}_+;$$

in particular, the right tail of $P_k^{(N)}$ decays doubly exponentially fast in the limit as $N \to \infty$. This behavior is a substantial improvement over the case $D = 1$, where $P_k^{(N)}$ decays exponentially, and has led to substantial interest in JSQ networks in the literature. For other references, see Azar et al. [1], Graham [8], Luczak-McDiarmid [9], Martin-Suhov [11], Mitzenmacher [12], Suhov-Vvedenskaya [14], Vocking [15] and Vvedenskaya-Suhov [17].

Little work has been done on the behavior of JSQ networks when the service times are not exponentially distributed. In this setting, the underlying Markov process will typically have an uncountable state space, and positive Harris recurrence for the process is no longer obvious. The latter was shown in Foss-Chernova [7], and uniform bounds on the equilibria were shown in Bramson [3]. (Both articles also considered JSQ networks with more general arrivals and routing of jobs.)

An important first step in analyzing the limiting behavior of the equilibria, as $N \to \infty$, is to show that any fixed number of queues become independent of one another and converge to a limiting distribution. Moreover, one wishes to show that such a limiting distribution is the unique equilibrium for an associated Markov process at a single queue, the environment process, which corresponds in an appropriate sense to “setting $N = \infty$” and viewing the corresponding infinite dimensional process at a single queue. We will refer to this equilibrium as the equilibrium environment. In Section 2, we will precisely define this terminology.

Although it seems that this independence should hold in a very general setting, including under a wide range of service disciplines, demonstrating
it appears to be a difficult problem. In Bramson et al. [4], this independence and the corresponding behavior for the environment process were stated as an ansatz. This ansatz was demonstrated in Bramson et al. [5] in several settings including for networks where the service discipline is FIFO and the service distribution has a decreasing hazard rate.

In this article, we employ the restriction of the above ansatz to FIFO networks. This version of the ansatz will be precisely stated in Section 2. Here, we summarize it for application in the current section:

For a family of networks with the FIFO service discipline that are all in equilibrium, any fixed number of queues become independent in the limit as $N \to \infty$. Moreover, each marginal distribution converges to the unique associated equilibrium environment.

Although this ansatz has only been demonstrated for service distributions having decreasing hazard rate and for general service distributions with sufficiently small $\alpha$ for arrivals, our arguments here do not otherwise require either restriction. Other applications of the ansatz, but for the processor sharing and LIFO service disciplines, are given in [4].

Our goal, in this article, is to investigate the limiting behavior of the right tail of the associated equilibrium environment, under the FIFO service discipline and with the assigned mean-1 service distribution $F(\cdot)$. Denote by $P_k$ the probability that there are at least $k$ jobs in the equilibrium environment. We will show that, when $F(\cdot)$ has a power law tail with exponent $-\beta$, for given $\beta > 1$, the tail of $P_k$ exhibits a wide range of behavior depending on the relationship between $\beta$ and $D$. In particular, if $\beta > D/(D-1)$, the tail is doubly exponential and, if $\beta < D/(D-1)$, the tail has a power law; when $\beta = D/(D-1)$, the tail is exponentially distributed. When $\beta \nearrow \infty$, the coefficient $q_D(\beta)$ of $k$ in the doubly exponential tail converges to 1, which is the coefficient of $k$ in (1.1). One obtains the same coefficient of $k$ when $F(\cdot)$ has an exponential tail or has bounded support. Our main results are Theorems 1.1, 1.2 and 1.3. Theorem 1.1 covers the case $\beta > D/(D-1)$, Theorem 1.2 covers the case $\beta < D/(D-1)$ and Theorem 1.3 covers the case $\beta = D/(D-1)$. We set $\bar{F}(s) = 1 - F(s)$.

**Theorem 1.1.** Consider a family of JSQ networks, with given $D \geq 2$ and $N = D, D + 1, \ldots$, where the $N$th network has Poisson rate-$\alpha N$ input, with $\alpha < 1$, and where service at each queue is FIFO, with distribution $F(\cdot)$
having mean 1. Assume that (1.2) holds and that

\[(1.3) \quad \lim_{s \to \infty} \log \bar{F}(s)/\log s = -\beta,\]

with \(\beta \in (D/(D - 1), \infty).\) Then,

\[(1.4) \quad \lim_{k \to \infty} (1/k) \log_D (1/P_k) = q_D(\beta)\]

for some \(q_D(\beta) \in (0, 1).\) Moreover, \(q_D(\beta)\) is continuous in \(\beta\) and

\[(1.5) \quad q_D(\beta) \nearrow 1 \quad \text{exponentially fast as } \beta \nearrow \infty.\]

When (1.3) holds with \(\beta = \infty,\) then (1.4) holds with \(q_D(\infty) = 1.\)

Theorem 1.1 implies that, when \(\bar{F}(s) \sim cs^{-\beta}\) as \(s \to \infty,\) for \(\beta \in (D/(D - 1), \infty)\) and \(c > 0,\) then \(P_k = \exp\{-D^{(1+o(1))q_D(\beta)k}\}.

**Theorem 1.2.** Consider a family of JSQ networks as in Theorem 1.1, with (1.3) instead holding for \(\beta \in (1, D/(D - 1)).\) Then

\[(1.6) \quad \lim_{k \to \infty} (1/k) \log (1/P_k)/\log k = (\beta - 1)/[1 - (D - 1)(\beta - 1)].\]

Theorem 1.2 implies that, when \(\bar{F}(s) \sim cs^{-\beta}\) as \(s \to \infty,\) for \(\beta \in (1, D/(D - 1))\) and \(c > 0,\) then \(P_k = k^{-(1+o(1))\gamma_D(\beta)},\) where \(\gamma_D(\beta)\) is the right hand side of (1.6). Note that \(\gamma_D(\beta) \searrow 0 \text{ as } \beta \searrow 1 \text{ and } \gamma_D(\beta) \nearrow \infty \text{ as } \beta \nearrow D/(D - 1).\)

**Theorem 1.3.** Consider a family of JSQ networks as in Theorem 1.1, with (1.3) replaced by

\[(1.7) \quad c_1 \leq \lim_{s \to \infty} s^{D/(D - 1)} \bar{F}(s) \leq \lim_{s \to \infty} s^{D/(D - 1)} \bar{F}(s) \leq c_2\]

for some \(0 < c_1 \leq c_2 < \infty.\) Then, for appropriate \(r_D(c_2) > 0\) and \(s_D(c_1) < \infty,\)

\[(1.8) \quad r_D(c_2) \leq \lim_{k \to \infty} (1/k) \log (1/P_k) \leq \lim_{k \to \infty} (1/k) \log (1/P_k) \leq s_D(c_1),\]

where

\[(1.9) \quad r_D(c_2) \nearrow \infty \quad \text{as } c_2 \searrow 0,\]

\(s_D(c_1) \searrow 0 \quad \text{as } c_1 \nearrow \infty.\)
Theorem 1.3 implies that when \( \bar{F}(s) \sim cs^{-D/(D-1)} \) as \( s \to \infty \), then \( P_k \) decreases exponentially fast in the sense of (1.8). Because of (1.9), the exponent depends strongly on the choice of \( c \).

We note that the proofs of Theorems 1.1-1.3 only depend on (1.2) for the existence of an equilibrium environment. Regardless of how the existence of an equilibrium environment is verified, (1.2) is needed in order to relate the tail behavior of \( P_k \) for the equilibrium environment to the tail behavior for the equilibria of the corresponding family of networks as \( N \to \infty \).

This article is organized as follows. In Section 2, we provide basic background on the properties of the state space and Markov process that underlie the JSQ networks. We then define equilibrium environments and formally state the ansatz. In Sections 3-5, we demonstrate Theorems 1.1, 1.2 and 1.3, respectively. Our approach will be to demonstrate lower bounds and then upper bounds that yield the theorem. In each case, the lower bounds will be considerably easier to show.

**Notation.** For the reader’s convenience, we mention here some of the notation in the paper. We will employ \( C_1, C_2, \ldots \) to denote positive constants whose precise value is not of importance to us. For \( z \in \mathbb{R} \), \( \lfloor z \rfloor \) and \( \lceil z \rceil \) will denote the integer part of \( z \), respectively, the smallest integer at least as large as \( z \).

2. Markov process background, equilibrium environments and the ansatz. In this section, we provide a more detailed description of the construction of the Markov processes \( X^{(N)}(\cdot) \) that underlie the JSQ networks. We next define the corresponding cavity process and its equilibrium environment. We then employ these concepts to state the ansatz for JSQ networks. Most of this material is included in Sections 2 and 3 of Bramson et al. [5]. (Related material is also given in [2] and [3].)

We define the state space \( S^{(N)} \) to be the set

\[
(\mathbb{Z} \times \mathbb{R}^2)^N.
\]

The first coordinate \( z^n, n = 1, \ldots, N \), corresponds to the number of jobs at the \( n \)th queue; the second coordinate \( u^n, u^n \geq 0 \), is the amount of time the oldest job there has already been served; and the last coordinate \( s^n, s^n > 0 \), is the residual service time. When \( z^n = 0 \), set the other two coordinates equal to 0. The coordinate \( u^n \) will not play a role in the evolution of \( X^{(N)}(\cdot) \) here; we retain it for comparison with [5], where it was used to demonstrate (1.2) under decreasing hazard rates. (We will employ slightly different notation here than in [5].)
For given \( N' \leq N \), \( S^{(N')} \) is the projection of \( S^{(N)} \) obtained by restricting \( S^{(N)} \) to the first \( N' \) queues; for \( x \in S^{(N)}, x' \in S^{(N')} \) is thus obtained by omitting the coordinates with \( n > N' \). One can also define projections of \( S^{(N)} \) onto spaces \( S^{(N')} \) corresponding to other subsets of \( \{1, \ldots, N\} \) analogously, although these are not needed here.

We define the metric \( d^{(N)}(\cdot, \cdot) \) on \( S^{(N)} \), with \( d^{(N)}(\cdot, \cdot) \) given in terms of \( d^{(N),n}(\cdot, \cdot) \) by \( d^{(N)}(\cdot, \cdot) = (1/N) \sum_{n=1}^{N} d^{(N),n}(\cdot, \cdot) \). For given \( x_1, x_2 \in S^{(N)} \), with the coordinates labelled correspondingly, set

\[
(2.2) \quad d^{(N),n}(x_1, x_2) = |z^n_1 - z^n_2| + |u^n_1 - u^n_2| + |s^n_1 - s^n_2|.
\]

One can check that the metric \( d^{(N)}(\cdot, \cdot) \) is separable and locally compact; more detail is given on page 82 of [2]. We equip \( S^{(N)} \) with the standard Borel \( \sigma \)-algebra inherited from \( d^{(N)}(\cdot, \cdot) \), which we denote by \( \mathcal{S}^{(N)} \).

The Markov process \( X^{(N)}(t) \), \( t \geq 0 \), underlying a given model is defined to be the right continuous process with left limits, taking values \( x \) in \( S^{(N)} \), whose evolution is determined by the model together with the assigned service discipline. We denote the random values of the coordinates \( z^n \), \( u^n \) and \( s^n \) taken by \( X^{(N)}(t) \), by \( Z^n(t) \), \( U^n(t) \) and \( S^n(t) \). Jobs are allocated service according to the FIFO discipline; during the period a job is being served, \( U^n(t) \) increases at rate 1 and \( S^n(t) \) decreases at rate 1.

Along the lines of page 85 of [2], a filtration \( (\mathcal{F}^{(N)}_t) \), \( t \in [0, \infty] \), can be assigned to \( X^{(N)}(\cdot) \) so that \( X^{(N)}(\cdot) \) is a piecewise-deterministic Markov process, and hence is Borel right. This implies that \( X^{(N)}(\cdot) \) is strong Markov. (We do not otherwise use Borel right.) The reader is referred to Davis [6] for more detail.

**Equilibrium environments and the ansatz.** In order to state the ansatz, we require some terminology. We denote by \( \mathcal{E}^{(N,N')} \) the projection of the equilibrium measure \( \mathcal{E}^{(N)} \) of the \( N \)-queue system onto the first \( N' \) queues. (Since \( X^{(N)}(t) \) is exchangeable when \( X^{(N)}(0) \) is, the choice of queues will not matter.)

We wish to describe the evolution of individual queues for the limiting process, as \( N \to \infty \). For this, we construct a strong Markov process \( X^H(t), t \geq 0 \), on \( S^{(1)} \) as follows. Let \( \mathcal{H} \) denote a probability measure on \( S^{(1)} \), which we refer to as the environment of the process \( X^H(\cdot) \); we refer to \( X^H(\cdot) \) as the associated cavity process. We define \( X^H(\cdot) \) so that potential arrivals arrive according to a rate–\( \alpha \) Poisson process. When such a potential arrival to the queue occurs at time \( t \), \( X^H(t-) \) is compared with the states of \( D - 1 \) independent random variables, each with law \( \mathcal{H} \); we refer to these \( D - 1 \) states at a potential arrival as the comparison states. Choosing from among
these $D$ states, the job is assigned to the state with the fewest number of jobs. (In case of a tie, each of these states is chosen with equal probability.) If the job has chosen the state $X^H(t-)$ at the queue, it then immediately joins the queue; otherwise, the job immediately leaves the system. In either case, the independent $D-1$ states employed for this purpose are immediately discarded. Jobs in the cavity process $X^H(\cdot)$ have the same service distribution $F(\cdot)$ as in the queueing network and are served according to the FIFO service discipline. The number of jobs in $X^H(t)$ will be denoted by $Z^H(t)$, the amount of time the oldest job has already been served by $U^H(\cdot)$ and the residual service time by $S^H(t)$; we will employ $x$, $z$, $u$ and $s$ for the corresponding terms in the state space.

When a cavity process $X^H(\cdot)$, with environment $H$, is stationary with the equilibrium measure $H$ (i.e., $X^H(t)$ has the distribution $H$ for all $t$), we say that $H$ is an equilibrium environment. One can think of an equilibrium environment as being the restriction of an equilibrium measure for the JSQ network, viewed at a single queue, when “the total number of queues $N$ is infinite”.

We now state the ansatz. Here, $\overset{\nu}{\rightarrow}$ on $S^{(N')}$ denotes convergence in total variation with respect to the metric $d_{N'}(\cdot,\cdot)$ on $S^{(N')}$. 

\textbf{Ansatz} . Consider a family of JSQ networks, with given $D \geq 2$ and $N = D, D+1, \ldots$, where the $N$th network has Poisson rate-$\alpha N$ input, with $\alpha < 1$, and where service at each queue is FIFO, with distribution $F(\cdot)$ having mean 1. Then, (a) for each $N'$,

\begin{equation}
E^{(N,N')} \overset{\nu}{\rightarrow} E^{(\infty,N')} \quad \text{as } N \rightarrow \infty,
\end{equation}

where $E^{(\infty,N')}$ is the $N'$-fold product of $E^{(\infty,1)}$. Moreover, (b) $E^{(\infty,1)}$ is the unique equilibrium environment associated with this family of networks.

As was mentioned in the introduction, this ansatz was demonstrated in Bramson et al. [5] when the service time distribution $F(\cdot)$ has a decreasing hazard rate $h(\cdot)$ (i.e., $h(s) = F'(s)/\bar{F}(s)$ is nonincreasing in $s$) and for general service distributions when the arrival rates are small enough.

In order to demonstrate Theorems 1.1-1.3, we will analyze the cavity process $X^H(\cdot)$ with its unique equilibrium environment $H = E^{(\infty,1)}$. In particular, we will analyze $E^{(\infty,1)}$ over a cycle starting and ending at the state 0. (The state where the number of jobs $z$ is 0.) Letting $\nu$ denote the time at which $X^H(\cdot)$ first returns to 0 after visiting another state, the first cycle is the random time interval $[0,\nu]$. For any $k \geq 1$, we will denote by $V_k$ the
occupation time at states $x$, with $z \geq k$, over $[0, \nu]$, that is,

$$V_k = \int_0^\nu 1\{Z^H(t) \geq k\} \, dt.$$ 

Setting $m_0 = E[\nu]$, the mean return time to 0, one has

$$P_k = m_0^{-1} E[V_k],$$

where $P_k$ is the probability there are at least $k$ jobs in the equilibrium environment.

Let $\alpha_k$ denote the arrival rate of jobs for $X^H(\cdot)$, when $z = k$. In order for a potential arrival to arrive at the queue, it is necessary for all of the $D-1$ comparison states used at that time to be at least $k$, in which case the probability of selecting the queue is the reciprocal of the number of states equal to $k$. This gives the bounds

$$\alpha P_k^{D-1} \leq \alpha_k \leq \alpha D P_k^{D-1}. \tag{2.5}$$

Since the departure of jobs from the queue is deterministic, being a function of the residual service time $s$, (2.5) gives a reasonably explicit description of the transition rates for $X^H(\cdot)$. Together with (2.4), (2.5) will provide the basis for our demonstration of Theorems 1.1-1.3 and will be used throughout the paper.

3. The case where $\beta > D/(D - 1)$. In this section, we demonstrate Theorem 1.1; we do this by demonstrating lower and upper bounds that are needed for the theorem in Propositions 3.1 and 3.2. Each of these bounds is expressed in terms of a recursion relation for $P_k$. In order to obtain Theorem 1.1 from these recursions, we employ Proposition 3.3, which analyzes such recursions by utilizing a standard framework involving rational generating functions. The section is organized as follows. After stating Propositions 3.1 and 3.2, we state and prove Proposition 3.3. We next employ the three propositions to demonstrate Theorem 1.1. We then provide the relatively quick proof of Proposition 3.1 and the longer proof of Proposition 3.2, in the following subsections.

In both propositions, we set $k_1 = \lceil k - \beta \rceil$ (or, equivalently, $\lfloor \beta \rfloor = k - k_1$) and $\hat{\beta} = \beta - \lfloor \beta \rfloor$.

**Proposition 3.1.** Consider a family of JSQ networks, with given $D \geq 2$ and $N = D, D+1, \ldots$, where the $N$th network has Poisson rate-$\alpha N$ input, with $\alpha < 1$, and where service at each queue is FIFO, with distribution $F(\cdot)$.
having mean 1. Assume that (1.2) holds. Then, for appropriate $C_1 > 0$ and all $k$,  

$$
(3.1) \quad P_k \geq (C_1/8k)^k \prod_{i=0}^{k-1} P_i^{D-1}.
$$

If moreover, for some $s_0 \geq 1$,  

$$
(3.2) \quad \bar{F}(s) \geq s^{-\beta} \quad \text{for } s \geq s_0,
$$

with $\beta \in (D/(D - 1), \infty)$, then, for appropriate $C_1 > 0$ and all $k$,  

$$
(3.3) \quad P_k \geq C_1 3^{-k} \left( \prod_{i=k_1 + 1}^{k-1} P_i^{D-1} \right) P_{k_1}^\beta(D-1).
$$

**Proposition 3.2.** Consider a family of JSQ networks, with given $D \geq 2$ and $N = D, D + 1, \ldots$, where the $N$th network has Poisson rate-$\alpha N$ input, with $\alpha < 1$, and where service at each queue is FIFO, with distribution $F(\cdot)$ having mean 1. Assume that (1.2) holds and that, for some $s_0 \geq 1$,  

$$
(3.4) \quad \bar{F}(s) \leq s^{-\beta} \quad \text{for } s \geq s_0,
$$

with $\beta \in (D/(D - 1), \infty)$. If $\beta$ is not an integer, then, for appropriate $C_2$ and all $k$,  

$$
(3.5) \quad P_k \leq C_2 k^{\beta + 1} \left( \prod_{i=k_1 + 1}^{k-1} P_i^{D-1} \right) P_{k_1}^\beta(D-1).
$$

If $\beta$ is an integer, then, for each $\delta > 0$, appropriate $C_2$ and all $k$,  

$$
(3.6) \quad P_k \leq C_2 k^{\beta + 1} \left( \prod_{i=k_1 + 2}^{k-1} P_i^{D-1} \right) P_{k_1+1}^{(1-\delta)(D-1)}.
$$

To employ the recursions in (3.3) and (3.5)–(3.6) of Propositions 3.1 and 3.2 in the proof of Theorem 1.1, we will analyze the asymptotic behavior of the recursions in (3.7).

**Proposition 3.3.** Suppose that $R_k$ satisfies  

$$
(3.7) \quad R_k = (D - 1) \left( \sum_{i=k-\ell+1}^{k-1} R_i + \eta R_{k-\ell} \right) \quad \text{for } k \geq 1,
$$
with $R_k = 1$ for $k = -\ell +1, \ldots, -1,0$, $D \geq 2$ and $\eta \in [0,1]$. Then, setting $\beta = \ell + \eta -1$,

\begin{equation}
\lim_{k \to \infty} \frac{1}{k} \log_d R_k = q_D(\beta)
\end{equation}

for some $q_D(\beta) \in (0,1)$. Moreover, $q_D(\beta)$ is continuous in $\beta$ and $q_D(\beta) \nearrow 1$ exponentially fast as $\beta \nearrow \infty$.

**Proof.** The recurrence (3.7) is a special case of linear recursions of the form

\begin{equation}
R_k + \sum_{i=1}^{\ell} a_i R_{k-i} = 0,
\end{equation}

with $a_i \in \mathbb{C}$ and general $R_{-\ell+1}, \ldots, R_0$. It is well known that (see, e.g., Stanley [13], page 202)

\begin{equation}
R_k = \sum_{i=1}^{j} P_i(k) \gamma_i^k
\end{equation}

for each $k$, where $\gamma_i$ are distinct, $P_i(k)$ is a polynomial in $k$ of degree strictly less than $\ell_i$, and

\begin{equation}
1 + \sum_{i=1}^{\ell} a_i x^i = \prod_{i=1}^{j} (1 - \gamma_i x)_{\ell_i},
\end{equation}

with $\sum_{i=1}^{j} \ell_i = \ell$. Moreover the converse holds, that is, if (3.10) and (3.11) both hold, then so does (3.9).

For $R_k$ given by (3.7), it is not difficult to check that there is exactly one value $\gamma_i$, say $\gamma_1$, that is real and positive, that $\gamma_1$ varies continuously in $\eta$, and moreover that $\gamma_1$ satisfies $\gamma_1 > 1$, since $a_i < 0$ and $\sum_{i=1}^{\ell} a_i < -1$. (Descartes’ rule of signs in fact implies that $1/\gamma_1$ is a simple root.) Also, because $a_i < 0$, and possesses both odd and even indices, $|\gamma_i| < \gamma_1$ for $i \neq 1$. Since the initial data given below (3.7) are all positive, any solution of (3.7) is majorized by this particular solution, up to a multiplicative constant; so, $P_1(\cdot) \neq 0$. The limit in (3.8), with $q_D(\beta) = \log_d \gamma_1 > 0$, follows from these observations.

We still need to examine the limiting behavior of $q_D(\beta)$ as $\beta \to \infty$. Dividing both sides in (3.7) by $R_k$, then substituting (3.10) for each of the terms, and letting $k \to \infty$ implies that

$1 = (D-1) \left( x + x^2 + \ldots + x^{\ell-1} + \eta x^\ell \right)
= (D-1) \left( x - (1-\eta)x^\ell - \eta x^{\ell+1} \right) / (1-x)$
JOIN THE SHORTEST QUEUE

11

for $x = 1/\gamma_1 = D^{-q_D(\beta)}$. This again uses $\gamma_1 > |\gamma_i|$ for $i \neq 1$. Hence,

$$Dx - 1 = (D - 1) \left( (1 - \eta)x^\ell + \eta x^{\ell+1} \right).$$

(3.12)

Note that $x \in (0,1)$ and that, since $q_D(\beta)$ is increasing in $\beta$, $x$ is decreasing in $\beta$. Since the right hand side goes to 0 exponentially fast as $\ell \to \infty$, and hence as $\beta \to \infty$, it follows that $x \downarrow 1/D$ exponentially fast as $\beta \to \infty$, which also implies $q_D(\beta) \to 1$ exponentially fast, as desired. Note that the precise exponential rate of convergence can be obtained by inserting this limit back into the right hand side of (3.12).

Applying Proposition 3.3 to Propositions 3.1 and 3.2, we now demonstrate Theorem 1.1.

PROOF OF THEOREM 1.1. Setting $Q_k = e^{-R_k}$, where $R_k$ is given in (3.7), one has

$$Q_k = \left( \prod_{i=k-\ell+1}^{k-1} Q_i^{D-1} \right) Q_k^{\eta(D-1)},$$

(3.13)

with $Q_k = e$ for $k = -\ell + 1, \ldots, -1, 0$. We proceed to compare $Q_k$ with $1/P_k$, where $P_k$ satisfies one of (3.3), (3.5) and (3.6).

Comparison of $Q_k$ with $1/P_k$, with $\eta = \hat{\beta}$, $\ell = \lceil \beta \rceil = k - k_1$ and $P_k$ satisfying (3.3), provides an upper bound on the limit in (1.4). To see this, we first set $\tilde{Q}_k = M^{-k}Q_k$, for given $M > 1$. Since $(D-1)(\beta-1) > 1$, by substituting into (3.13), one can check that, for large enough $M$ and $k$,

$$\tilde{Q}_k \geq C_3b^k \left( \prod_{i=k-\ell+1}^{k-1} \tilde{Q}_i^{D-1} \right) \tilde{Q}_k^{\eta(D-1)}$$

(3.14)

for any fixed choice of $C_3$ and $b$, in particular, for $C_3 = 1/C_1$ and $b = 3$, where $C_1$ is chosen as in Proposition 3.1. Moreover, on account of (3.8),

$$\lim_{k \to \infty} \left( \frac{1}{k} \log D \log (\tilde{Q}_k) \right) = q_D(\beta)$$

(3.15)

where, in particular, $q_D(\beta) > 0$, and hence $\tilde{Q}_k \to \infty$ as $k \to \infty$.

We observe that $1/P_k$ satisfies the inequality that is analogous to that for $P_k$ in (3.3), but with the inequality reversed and prefactors $3^k/C_1$ instead of $C_1/3^k$. Comparing $\tilde{Q}_k$ with $1/P_k$ therefore implies that, for large enough $n$ not depending on $k$,

$$1/P_k \leq \tilde{Q}_{k+n}.$$
The upper bound for (1.4) therefore follows from (3.15) for the same choice of $q_D(\beta)$, which we recall is continuous in $\beta$. The limit in (1.5) also follows from Proposition 3.3.

Comparison of $Q_k$ with $1/P_k$ also provides a lower bound on the limit in (1.4). In the case where $\beta$ is nonintegral, we choose $\eta$ and $\ell$ as before, with $\eta = \beta$, $\ell = \lfloor \beta \rfloor = k - k_1$; note that $P_k$ satisfies the upper bound in (3.5). We proceed as in the first part, but instead set $\tilde{Q}_k = M^k Q_k$, for given $M > 1$. One can check that, for large enough $M$ and $k$,

$$\tilde{Q}_k \leq C_3 b^k \left( \prod_{i=k-\ell+1}^{k-1} Q_i^{D-1} \right) Q_{k-\ell}^{(D-1)}$$

for any choice of $C_3 > 0$ and $b > 0$. As before, (3.15) holds.

The terms $1/P_k$ satisfy the inequality that is the analog of (3.5). Also, $1/P_k \to \infty$ as $k \to \infty$. Comparing $\tilde{Q}_k$ with $1/P_k$ therefore implies that, for large enough $n$ not depending on $k$,

$$\frac{1}{P_{k+n}} \geq \tilde{Q}_k.$$

The lower bound for (1.4) therefore follows from (3.15) when $\beta$ is nonintegral.

The reasoning in the case where $\beta$ is integral is similar, but with the difference that we now choose $\eta = 1 - \delta$, $\ell = \beta - 1 = k - k_1 - 1$, where $\delta \in (0, 1)$ is arbitrary. Now, $P_k$ satisfies the upper bound in (3.6). We proceed as in the nonintegral case, once again obtaining (3.16). Comparing $1/P_k$ with $\tilde{Q}_k$ again produces (3.15), except that the limit is now $q_D(\beta - \delta)$ because of our choice of $\eta$. By Proposition 3.3, $q_D(\cdot)$ is continuous in its argument.

Therefore, letting $\delta \to 0$ produces the same limit as in the nonintegral case, and hence implies the lower bound for (1.4) in the case where $\beta$ is integral.

We still need to demonstrate that when (1.3) holds with $\beta = \infty$, then (1.4) holds with $q_D(\infty) = 1$. The lower bound in (1.4) holds on account of (1.5). The upper bound is not difficult to show and does not require Proposition 3.3; we proceed to show the bound.

We will show by induction that, for all $k$,

$$P_k \geq (C_1/8k)^{kD^k},$$

where $C_1$ is as chosen as in (3.1), which we assume WLOG is at most 1. To see (3.18), note that if it holds for all $i = 0, \ldots, k - 1$ then this, together with (3.1), implies that

$$P_k \geq (C_1/8k)^k \prod_{i=0}^{k-1} \left[ (C_1/8i)^{D^i} \right]^{D-1} \geq (C_1/8k)^{(k-1)(D^k-1)+k} \geq (C_1/8k)^{kD^k}.$$
The upper bound in (1.4), with $q_D(\infty) = 1$, follows immediately from (3.18).

**Demonstration of Proposition 3.1.** The proof of Proposition 3.1 is quick. To obtain the lower bounds in both (3.1) and (3.3), it suffices to construct a path along which $Z^H(t)$ increases from 0 to $k$ within the first cycle. This is done, in both cases, by allocating the same amount of time to each of the first $k$ arrivals, which are also required to occur before the first departure.

**Proof of Proposition 3.1.** Consider the cavity process $X^H(\cdot)$ with $X^H(0) = 0$. In order to show (3.1) and (3.3), we obtain lower bounds on the expected amount of time $E[V_k]$ over which $Z^H(t) \geq k$ before $X^H(\cdot)$ returns to 0. We first show (3.1).

We consider the event $A$ where the first service time $S$ is at least $1/2$ and the first $k$ arrivals occur by time $1/4$. The latter event contains the event where each of the first $k$ arrivals occurs not more than $1/4k$ units of time after the previous arrival, starting at time 0.

Conditioned on there being $i$ jobs in the queue, jobs arrive at rate $\alpha_i \geq \alpha P D_i - 1$, and so the probability of such an arrival occurring over an interval of length $1/4k$ is at least $1 - \exp\{-\alpha P D_i - 1/4k\}$. So, given that $S \geq 1/2$, the probability that all $k$ of these arrivals occur by time $1/4$ is at least

$$
(3.19) \quad \prod_{i=0}^{k-1} \left(1 - \exp\{-\alpha P D_i - 1/4k\}\right).
$$

The event $S \geq 1/2$ occurs with some positive probability $c$ depending on $F(\cdot)$ and, under the event $A$, the departure time for the first job occurs at least $1/4$ after the last of the first $k$ arrivals. So, the expected amount of time in $[1/4, 1/2]$, during which $Z^H(t) \geq k$ and before $X^H(\cdot)$ has returned to 0, is at least

$$
(3.20) \quad \frac{c}{4} \prod_{i=0}^{k-1} \left(1 - \exp\{-\alpha P D_i - 1/4k\}\right),
$$

which is therefore a lower bound for $E[V_k]$. It therefore follows from (2.4) that

$$
(3.21) \quad P_k \geq \frac{c}{4m_0} \prod_{i=0}^{k-1} \left(1 - \exp\{-\alpha P D_i - 1/4k\}\right) \geq \frac{c}{4} (\alpha/8k)^k \prod_{i=0}^{k-1} P D_i - 1,
$$

which implies (3.1) for appropriate $C_1$. 

We next show (3.3) under the assumption (3.2). For this, we set

\begin{equation}
(3.22) \quad s_1 = 2k/(\alpha P_{k_1}^{D-1}).
\end{equation}

One can reason analogously as through (3.20), but by replacing the time interval \([0, 1/2]\) by \([0, s_1]\) and employing \(s_1/2k\) for the allotted time for each of the \(k\) arrivals. One obtains that the expected amount of time in \([s_1/2, s_1]\), during which \(Z^H(t) \geq k\) and before \(X^H(\cdot)\) has returned to 0, is at least

\begin{equation}
(3.23) \quad \frac{s_1}{2} F(s_1) \prod_{i=0}^{k-1} \left(1 - \exp\{-\alpha s_1 P_i^{D-1}/2k\}\right).
\end{equation}

Choose \(k\) large enough so that \(s_1 \geq s_0\), where \(s_0\) is as in (3.2) and \(s_1\) is as in (3.22). Since \(e^{-x} \leq (1 - x/2) \lor 1/2\) for \(x \geq 0\), this is at least

\begin{equation}
2^{-(k+1)}s_1^{-\beta-1}(\alpha s_1/4k)^{k-k_1-1} \prod_{i=k_1+1}^{k-1} P_i^{D-1}
\geq 2^{-k}(\alpha/4k)^{\beta} \left( \prod_{i=k_1+1}^{k-1} P_i^{D-1} \right) P_{k_1}^{\hat{\beta}(D-1)},
\end{equation}

where the inequality follows from (3.22) and \(k - k_1 = \beta - \hat{\beta}\). Consequently,

\begin{equation}
E[V_k] \geq 2^{-k}(\alpha/4k)^{\beta} \left( \prod_{i=k_1+1}^{k-1} P_i^{D-1} \right) P_{k_1}^{\hat{\beta}(D-1)}.
\end{equation}

Again applying (2.4), it follows that, for large enough \(k\) (depending on \(\alpha\) and \(\beta\)),

\begin{equation}
P_k \geq 3^{-k} \left( \prod_{i=k_1+1}^{k-1} P_i^{D-1} \right) P_{k_1}^{\hat{\beta}(D-1)},
\end{equation}

which implies (3.3). \(\square\)

**Demonstration of Proposition 3.2.** In order to demonstrate Proposition 3.2, we will employ Lemma 3.1 below; the lemma will also be employed in the demonstration of Propositions 4.2 and 5.2. Lemma 3.1 provides upper bounds involving \(R(k, s)\), \(H(n)\) and \(p(k, s)\), for \(k \geq 1\), \(s \geq 0\) and \(n \geq 0\), which we define as follows. For \(s > 0\), \(R(k, s)\) is the expected return time of the cavity process \(X^H(\cdot)\) to the empty state 0, from \(X^H(0)\) with \(Z^H(0) = k\) and \(S^H(0) = s\). We set \(R(k, 0) = \lim_{s \to 0} R(k, s)\), which is also the expected
return time to 0 just after departure of a job, but without knowledge of the residual service time of the job that is beginning service. The quantity $H(n)$ is the number of jobs, for this process, at the time when the $(n+1)$st job has just departed, e.g., $H(0)$ is the number of jobs just after departure of the job originally in service. The stopping time $\rho(k, s)$ is the first time $n$ at which $H(n) = 0$. We also denote by $Y_n$ the service time of the $(n+1)$st job (with $Y_0 = s$ being the service time of the job originally in service), and set $T_\ell = \sum_{n=0}^{\ell} Y_n = \sum_{n=1}^{\ell} Y_n + s$. Note that $Y_1, Y_2, \ldots$ are i.i.d. with distribution function $F(\cdot)$, which, as always, is assumed to have mean 1.

**Lemma 3.1.** Let $R(\cdot, \cdot)$ and $\rho(\cdot, \cdot)$ be defined as above. Then, for large enough $N_0$,

\begin{equation}
R(k, s) \leq 2(k + s + N_0)
\end{equation}

and

\begin{equation}
E[\rho(k, s)] \leq 2(k + s/2 + N_0),
\end{equation}

for all $k$ and $s$.

**Proof.** It is not difficult to see that (3.24) follows from (3.25). By applying Wald’s equation to $T(\cdot)$ and $\rho(\cdot, \cdot)$ (with respect to the underlying $\sigma$-algebra generated by $X^{N}(\cdot)$), one obtains

$$ R(k, s) = E[T_{\rho(k, s)}] = E \left[ \sum_{n=1}^{\rho(k, s)} Y_n \right] + s = E[\rho(k, s)]E[Y_1] + s \leq 2(k + s + N_0), $$

with the inequality following from (3.25) and $E[Y_1] = 1$.

In order to show (3.25), we consider the process

\begin{equation}
M(n) = H(n) + n/2 - N_1 \exp\{-\theta(H(n) \land k_0)\}.
\end{equation}

For appropriate choices of $N_1, \theta > 0$ and $k_0 \in \mathbb{Z}_+$, we claim $M(n)$ is a supermartingale, with respect to the filtration $\mathcal{G}_n = \sigma(H(0), \ldots, H(n))$, after restricting to times $n$, with $n \leq \rho(k, s)$, and then stopping the process.

These three constants are chosen as follows. We choose $k_0$ large enough so that $\alpha DP_{k_0+1}^{D-1} \leq 1/2$. For $H(n) > k_0$, one can check that the supermartingale inequality

\begin{equation}
E[M(n + 1)| \mathcal{G}_n] \leq M(n)
\end{equation}

for $n < \rho(k, s)$.
is satisfied – the arrival rate of jobs is at most $1/2$ over the time interval $(T_{n-1}, T_n]$ during which the $(n+1)$st job is served, which has mean length 1, and so

$$E[H(n+1) | G_n] \leq H(n) - 1/2.$$  

In order to analyze $M(n+1)$ when $H(n) \leq k_0$, we set

$$M_1(n) = -\exp\{-\theta(H(n) \wedge k_0)\}.$$  

We choose $\theta$ large enough so that, for some $\epsilon > 0$ and all $H(n) \leq k_0$,

$$E[M_1(n+1) | G_n] \leq M_1(n) - \epsilon.  \tag{3.28}$$

This requires a standard computation using the convexity of the exponential function and the upper bound $\alpha D$ on the arrival rate of jobs. (Since $H(\cdot)$ may have positive drift, $\theta$ may need to be chosen large.)

We also choose $N_1$ so that $\epsilon N_1 \geq \alpha D + 1/2$. Together with (3.28), this implies (3.27) also holds for $H(n) \leq k_0$. Consequently, $M(n)$ is a supermartingale, as claimed.

In order to demonstrate (3.25), we will apply the optional sampling theorem to $M(\cdot)$ stopped at times $\rho_n(k,s) = \rho(k,s) \wedge n$. First note that

$$E[M_1(0)] \leq E[H(0)] \leq k + s/2  \tag{3.29}$$

for $k \geq k_0$, since the arrival rate of jobs is bounded above by $1/2$. Also, for given $s$, $E[H(0)]$ is increasing as a function of $k$, the number of jobs in the cavity process at time 0. Together with (3.29), this implies that, for all $k$,

$$E[M(0)] \leq (k \vee k_0) + s/2 \leq k + s/2 + k_0.  \tag{3.30}$$

Since the supermartingale $M(\cdot)$ is bounded from below, application of the optional sampling theorem to $\rho_n(k,s)$ implies that

$$E[M(\rho_n(k,s))] \leq E[M(0)] \leq k + s/2 + k_0,$$

and hence

$$0 \leq E[H(\rho_n(k,s))] \leq k + s/2 + k_0 + N_1 - E[\rho_n(k,s)]/2.$$  

Solving for $E[\rho_n(k,s)]$ implies

$$E[\rho_n(k,s)] \leq 2(k + s/2 + k_0 + N_1) = 2(k + s/2 + N_0)$$

for $N_0 = k_0 + N_1$. Letting $n \to \infty$ implies (3.25).
Lemma 3.1 provides an upper bound on the expected time over a cycle during which there are at least $k$ jobs, provided such a state has already been attained. Below, we will obtain an upper bound on the probability of attaining such a state and combine this with (3.24).

In order for $X^H(\cdot)$, starting at 0, to attain a state with $k$ jobs, it must first attain states with $k_1 + 1, k_1 + 2, \ldots, k - 1$ jobs, where $k_1$ has been specified in the previous subsection. (It turns out that including states with fewer jobs in this sequence will not improve our bounds.) We let $\sigma_{k_1 + 1}, \ldots, \sigma_k$ denote the number of jobs that have already departed when such a state is first attained (e.g., $\sigma_i = 0$ means that the first job is still being served at the time $t$ when $Z^H(t) = i$ first occurs).

One trivially has $0 \leq \sigma_{k_1 + 1} \leq \sigma_{k_1 + 2} \leq \ldots \leq \sigma_k$. Partition $\{k_1 + 1, k_1 + 2, \ldots, k\}$ so that $i \neq i'$ are in the same subset if $\sigma_i = \sigma_{i'}$, i.e., the times $t_i$ and $t_{i'}$ at which $Z^H(t_i) = i$ and $Z^H(t_{i'}) = i'$ first occur are in the same service time interval. One can write such a partition as

\[(3.31) \quad \|i_0 + 1, \ldots, i_1\| \|i_1 + 1, \ldots, i_2\| \ldots \|i_{m-1} + 1, \ldots, i_m\|,\]

with $i_0 = k_1$ and $i_m = k$, when the partition consists of $m$ sets (where $m$ is random). We denote by $\Pi_k$ the set of all such partitions and by $\pi \in \Pi_k$ an element in the set, with the notation $i_0(\pi), i_1(\pi), \ldots, i_m(\pi)$ being used when convenient. We will say that a partition $\pi$ occurs during a cycle when the corresponding sequence of events occurs, and denote by $A_\pi$ the event associated with the partition.

For each of the sets in (3.31) except the last, there is a corresponding service interval, $[T_{n\ell-1}, T_{n\ell}]$, with $\ell = 1, \ldots, m - 1$, at the beginning of which there are strictly less than $i_\ell - 1$ jobs and at the end exactly $i_\ell$ jobs. (Since such an interval ends with a departure, the number of jobs at the beginning of the next service interval must be one less, which requires the cavity process to “retrace some of its steps” before the number of jobs reaches $i_\ell$ again.) For $\ell = m$, there may be strictly more than $k$ jobs at $T_{n\ell'}$; instead, we consider the restricted interval $[T_{nm-1}, \tau_k]$, where $\tau_k$ is the first time at which there are at least $k$ jobs. Unlike at the end of the other intervals $[T_{n\ell-1}, T_{n\ell}]$, the residual service time $s$ will not be 0. When $s$ is large, this will increase the occupation time where $Z^H(t) \geq k$, which will require us to exercise some care with our computations.

Since $k - k_1 \leq \beta$, the number of distinct partitions in (3.31) is at most $2^\beta$. In Proposition 3.4 below, we compute an upper bound on $P_k$ using an upper
bound on the expected occupation time corresponding to each partition, and then by multiplying by \(2^\beta\). The upper bound in (3.34) includes a factor \(k^\beta\) obtained by employing Lemma 3.1 repeatedly. The form of the bounds in (3.34) and (3.35) varies in different ranges of \(s\); we will therefore find it useful to employ the notation

\[
L_\ell(s) = \prod_{i=i_\ell-1}^{i_\ell-1} \left( \alpha D P_i^{D-1} s \right) \wedge 1.
\]

\(L_\ell(\cdot)\) implicitly depends on the partition \(\pi\) through \(i_\ell-1\) and \(i_\ell\). We will employ \(L(s)\) when \(i\) goes from \(k_1\) to \(k-1\), which corresponds to the trivial partition in (3.31) consisting of a single set.

In the proof of Proposition 3.4, we will use the following elementary Chebyshev integral inequality, which states that, if \(f(s)\) and \(g(s)\) are both integrable functions that are increasing in \(s\), then, for any distribution function \(F(\cdot)\),

\[
\int_{-\infty}^{\infty} f(s) g(s) F(ds) \geq \int_{-\infty}^{\infty} f(s) F(ds) \cdot \int_{-\infty}^{\infty} g(s) F(ds).
\]

**Proposition 3.4.** Consider a family of JSQ networks, with the same assumptions holding as in Proposition 3.2, except that (3.4) is not assumed. Then, for large enough \(k\),

\[
P_k \leq 3m_0^{-1}(6k)^{\beta} \int_{0}^{\infty} (k+s)L(s) F(ds).
\]

**Proof.** We first claim that the probability of the cavity process \(X^\mathcal{H}(\cdot)\), with \(Z^\mathcal{H}(0) \leq i_\ell-1\) and \(S^\mathcal{H}(0) = s\), attaining \(i_\ell\) jobs before time \(s\) is at most

\[
\prod_{i=i_\ell-1}^{i_\ell-1} \left( 1 - \exp\{-\alpha D P_i^{D-1} s\} \right) \leq \prod_{i=i_\ell-1}^{i_\ell-1} \left( (\alpha D P_i^{D-1} s) \wedge 1 \right) = L_\ell(s).
\]

Under this event, arrivals must occur sequentially over \([0,s]\) at times \(t_i\) when \(Z^\mathcal{H}(t_i-) = i\), for \(i = i_\ell-1, \ldots, i_\ell - 1\), and the rate of such arrivals is at most \(\alpha D P_i^{D-1}\). Since there is at most time \(s\) for each arrival, multiplying the corresponding upper bounds on the probability of an arrival at each step gives the first bound in (3.35). The following inequality is then obtained by applying the inequality \(1 - e^{-x} \leq x \wedge 1\).

Recall that \(V_k\) denotes the occupation time over a cycle when \(Z^\mathcal{H}(t) \geq k\). In order for \(V_k > 0\), the event \(A_\pi\) must occur for some \(\pi \in \Pi_k\); hence
\( E[V_k] = \sum_{\pi \in \Pi_k} E[V_k; A_\pi] \). We claim that, for any partition \( \pi \in \Pi_k \) and large enough \( k \),

\[
E[V_k; A_\pi] \leq (3k)^{m_\pi} \prod_{\ell=1}^{m_\pi-1} \left( \int_0^\infty L_\ell(s) F(ds) \right) \times 3 \int_0^\infty (k + s)L_{m_\pi}(s) F(ds).
\]

(3.36)

To obtain (3.36), we argue by induction, applying (3.35) at each step. It suffices to show that, for each step with \( \ell < m_\pi \), one obtains an additional factor \( 3i_{\ell-1} \int_0^\infty L_\ell(s) F(ds) \) and, for \( \ell = m_\pi \), one obtains the factor \( 9(i_{m_\pi-1}) \int_0^\infty (k + s)L_{m_\pi}(s) F(ds) \). For \( \ell \geq 2 \), the factor \( 3i_{\ell-1} \) is obtained by applying (3.25), with \( s = 0 \), which gives an upper bound on the expected number of service intervals occurring over the remainder of the cycle, after the service interval corresponding to the \((\ell - 1)\)st step ends; also, \( i_0 \geq m_0 \), which equals the expected number of service intervals at the beginning of the cycle. The other factor is obtained from (3.35) by integrating against \( F(\cdot) \) and, for \( \ell = m_\pi \), by employing (3.24) to provide an upper bound on the expected occupation time \( V_k \), again employing (3.35) and then integrating against \( F(\cdot) \).

On the other hand, by repeatedly applying the Chebyshev integral inequality (3.33) to (3.36), it follows that, for an arbitrary partition in (3.31), (3.36) is maximized for the trivial partition. That is, for any partition \( \pi \in \Pi_k \), the quantity in (3.36) is bounded above by

\[
3(3k)^\beta \int_0^\infty (k + s)L(s) F(ds).
\]

(3.37)

Since \(|\Pi_k| \leq 2^{\beta}\), it follows from (3.36) and (3.37) that

\[
P_k = m_0^{-1} E[V_k] = m_0^{-1} \sum_{\pi \in \Pi_k} E[V_k; A_\pi] \\
\leq 3m_0^{-1}(6k)^\beta \int_0^\infty (k + s)L(s) F(ds),
\]

which implies (3.34)

We now complete the proof of Proposition 3.2.

Proof of Proposition 3.2. We employ the upper bound for \( P_k \) given
by (3.34) for large enough $k$. The integral in (3.34) is bounded above by

$$2ks_0 \int_0^{s_0} L(s) F(ds) + 2k \int_{s_0}^{\infty} sL(s) F(ds)$$

(3.38)

$$\leq 2\beta(s_0^{\beta+1} + 1)k \int_{1}^{\infty} s^{-\beta} L(s) ds$$

by integrating by parts and absorbing the first term into the second; note that $L(s)$ is increasing in $s$ on account of (3.32). We decompose this last integral using intervals of the form $[1/\alpha DP_{k-1}^{D-1}, \infty)$, $[1/\alpha DP_{i-1}^{D-1}, 1/\alpha DP_{i}^{D-1})$, for $i = k_1 + 1, \ldots, k - 1$, and $[1, 1/\alpha DP_{k_1}^{D-1})$; we need to consider the cases where $\beta$ is and is not an integer separately.

Suppose that $\beta$ is not an integer. Applying (3.32) to the above integral over $[1/\alpha DP_{k-1}^{D-1}, \infty)$, one has the upper bound

$$\int_{1/\alpha DP_{k-1}^{D-1}}^{\infty} s^{-\beta} ds = \frac{1}{\beta - 1}(\alpha DP_{k-1})^{(D-1)(\beta-1)}.$$  

(3.39)

For $i = k_1 + 1, \ldots, k - 1$, one has, over $[1/\alpha DP_{i-1}^{D-1}, 1/\alpha DP_{i}^{D-1})$, the upper bounds

$$\int_{1/\alpha DP_{i-1}^{D-1}}^{1/\alpha DP_{i}^{D-1}} (\alpha Ds)^{k-i}(P_{k-1} \cdots P_i)^{D-1}s^{-\beta} ds$$

(3.40)

$$\leq \frac{(\alpha D)^{\beta-1}}{\beta + i - k - 1}(P_{k-1} \cdots P_i P_{\hat{\beta}+i-k-1})^{D-1}.$$  

For the last interval $[1, 1/\alpha DP_{k_1}^{D-1})$, one has the upper bound

$$\int_1^{1/\alpha DP_{k_1}^{D-1}} (\alpha Ds)^{k-k_1}(P_{k-1} \cdots P_{k_1})^{D-1}s^{-\beta} ds$$

(3.41)

$$\leq \frac{(\alpha D)^{\beta-1}}{1-\beta}(P_{k-1} \cdots P_{k_1+1} P_{\hat{\beta}})^{D-1},$$

where we recall that $\hat{\beta} = \beta - k + k_1$. Note that the lower limits of integration supply the dominant term in (3.39) and (3.40), whereas the upper limit supplies the dominant term in (3.41), because of the choice of $k_1$.

Since $P_i$ is decreasing in $i$, if one ignores the coefficients not involving powers of $P_i$ on the right hand sides of (3.39)–(3.41), the largest bounds in (3.39)–(3.41) are given in (3.40), with $i = k_1 + 1$, and in (3.41), in each case by the powers of $P_i$,

$$\left(P_{k-1} \cdots P_{k_1}^{\hat{\beta}}\right)^{D-1}.$$  

(3.42)
The coefficients of these powers are bounded above by terms not involving $k$. Employing (3.34) of Proposition 3.4, together with (3.38), one obtains the bound (3.5) for $P_k$, for appropriate $C_2$ and all $k$.

When $\beta$ is an integer, the computations are similar. The inequalities in (3.39) and (3.41) are the same as before, as are all of the cases in (3.40) except for $i = k_1 + 1$. Rather than (3.40), one obtains the following inequality when $i = k_1 + 1$:

\[
\int_{1/\alpha D^k_{k_1+1}}^{1/\alpha D^k_{k_1}} (\alpha Ds)^{\beta-1}(P_{k-1} \cdots P_{k_1+1})^{D-1}s^{-\beta} ds \\
\leq (D - 1)(\alpha D)^{\beta-1}(P_{k-1} \cdots P_{k_1+1})^{D-1} \log(P_{k_1}/P_{k_1+1}).
\]  

(3.43)

By comparing terms involving $P_i$ and ignoring the other coefficients, one can check that the largest bound is given in (3.43). Since the logarithm term there is dominated by $P_{k_1+1}^{-\delta(D-1)}$, for given $\delta > 0$ and small enough $P_{k_1+1}$, it follows that (3.6) holds for $P_k$, for appropriate $C_2$ and all $k$.

4. The case where $\beta \in (1, D/(D - 1))$. In this section, we demonstrate Theorem 1.2. We do this by demonstrating the lower and upper bounds needed for the theorem in Propositions 4.1 and 4.2. Here, we set $\nu_\beta = (\beta - 1)/[1 - (D - 1)(\beta - 1)]$.

Proposition 4.1. Consider a family of JSQ networks, with given $D \geq 2$ and $N = D, D + 1, \ldots$, where the $N$th network has Poisson rate-$\alpha N$ input, with $\alpha < 1$, and where service at each queue is FIFO, with distribution $F(\cdot)$ having mean 1. Assume that (1.2) holds and that

\[
\tilde{F}(s) \geq s^{-\beta} \quad \text{for } s \geq s_0,
\]

with $\beta \in (1, D/(D - 1))$ and some $s_0 \geq 1$. Then, for appropriate $C_4 > 0$ and all $k$,

\[
P_k \geq C_4k^{-\nu_\beta}.
\]  

(4.1)

Proposition 4.2. Consider a family of JSQ networks, with given $D \geq 2$ and $N = D, D + 1, \ldots$, where the $N$th network has Poisson rate-$\alpha N$ input, with $\alpha < 1$, and where service at each queue is FIFO, with distribution $F(\cdot)$ having mean 1. Assume that (1.2) holds and that

\[
\tilde{F}(s) \leq s^{-\beta} \quad \text{for } s \geq s_0,
\]

with $\beta \in (1, D/(D - 1))$ and some $s_0 \geq 1$. Then, for each $\delta > 0$, appropriate $C_5 > 0$, and all $k$,

\[
P_k \leq C_5k^{-1-(1-\delta)\nu_\beta}.
\]

(4.3)
Theorem 1.2 follows immediately from Propositions 4.1 and 4.2 upon letting $\delta \searrow 0$ in (4.4).

As in Section 3, the demonstration of the lower bound is much quicker than that of the upper bound. We first demonstrate the lower bound, Proposition 4.1, and then, in the remainder of the section, derive the upper bound, Proposition 4.2.

Demonstration of Proposition 4.1. As in Section 3, when we considered the case where $\beta > D/(D - 1)$, for the lower bound, it suffices to construct a path along which $Z^H(t)$ increases from 0 to $k$ within the first cycle. As before, we allocate the same amount of time for each of the first $k$ arrivals, which are also required to occur before the first departure.

Proof of Proposition 4.1. Consider the cavity process $X^H(\cdot)$ with $X^H(0) = 0$. We obtain a lower bound on the expected amount of time over which $Z^H(t) \geq k$ before $X^H(\cdot)$ returns to 0, assuming that $k \geq s_0$.

We consider the event where the first service time is at least $s_1 = \frac{4k}{(\alpha P_k^{D-1})}$ and the first $k$ arrivals occur by time $s_1/2$. We note that the probability of the latter event occurring is greater than the probability of at least $k$ events occurring by time $s_1/2$ for a rate-$\alpha P_k^{D-1}$ Poisson process, which, by a simple large deviations estimate, is at least

$$1 - e^{C_6 k} \geq 1/2$$

for large enough $k$ and an appropriate constant $C_6$. Together with (4.1), this implies that the expected amount of time in $[s_1/2, s_1]$, during which $Z^H(t) \geq k$ and before $X^H(\cdot)$ has returned to 0, is at least

$$\frac{1}{2} \cdot \frac{s_1}{2} \cdot \bar{F}(s_1) \geq \frac{1}{4} \left(\frac{4k}{(\alpha P_k^{D-1})}\right)^{-(\beta - 1)}.
$$

Inequality (4.5) implies that

$$P_k \geq \frac{\alpha}{16 m_0} k^{-(\beta - 1)} P_k^{(D-1)(\beta - 1)},$$

where $m_0$ is the mean return time to 0. Solving for $P_k$, it follows from this that, for large $k$,

$$P_k \geq \frac{\alpha}{16 m_0} k^{-\nu_\beta},$$

which implies (4.2) for all $k$. \qed
Demonstration of Proposition 4.2. The demonstration of the upper bound (4.4) for Theorem 1.2 is considerably more involved than is the lower bound. The basic idea is to consider two cases, depending on whether or not there is a service time \( s \) with \( s > s_1 \), for preassigned \( s_1 \geq 1 \), before a state \( x \) with \( z = k \) is reached in the first cycle, and to obtain upper bounds for each case. The two bounds are given in Propositions 4.3 and 4.4, which are then combined in Corollary 4.1. Employing Corollary 4.1, the proof of Proposition 4.2 provides an iteration scheme where a sequence of values \( s_1(n), n = 0, 1, 2, \ldots \), for \( s_1 \) are given that provide successively better upper bounds for \( P_k \), and that yield (4.4) in the limit. The demonstration of Proposition 4.4 involves the construction of a supermartingale, whose details are postponed until the end of the section.

Let \( \tau_k \), for given \( k \in \mathbb{Z}_+ \), denote the first time in the first cycle at which \( Z^H(t) = k \). For Propositions 4.3 and 4.4, we denote by \( B_{s_1,k} \) the set of realizations on which some service time that is strictly greater than \( s_1 \), with \( s_1 \geq 1 \), occurs up to and including the service time interval that contains \( \tau_k \). Proposition 4.3 considers the case where \( B_{s_1,k} \) occurs; the demonstration of the proposition is quick, using Lemma 3.1. As in Sections 2 and 3, we denote by \( V_k \) the occupation time at states \( x \), with \( z \geq k \).

**Proposition 4.3.** Consider a family of JSQ networks with the same assumptions holding as in Proposition 4.2. Then, for appropriate \( C_7 \) and all \( k \),

\[
E[V_k; B_{s_1,k}] \leq C_7 s_1^{-\beta}(k + s_1).
\]

**Proof.** We apply Lemma 3.1 at the beginning of the first service time that is greater than \( s_1 \). Since there are less than \( k \) jobs under \( B_{s_1,k} \) then, it follows that, for appropriate \( C_8 \) and large enough \( k \),

\[
E[V_k; B_{s_1,k}] \leq 3(P(B_{s_1,k})/\bar{F}(s_1)) \int_{s_1}^{\infty} (k + s) F(ds) \leq C_8 \int_{s_1}^{\infty} (k + s) F(ds).
\]

For the latter inequality, note that there are only a finite expected number of service times in the first cycle, and that, by Wald’s equation, the expected number of such times that are at most \( s \), for given \( s \geq 0 \), is proportional to \( F(s) \). Since \( k + s \) is increasing in \( s \), integration by parts together with (4.3) implies that the last quantity in (4.7) is at most \( C_7 s_1^{-\beta}(k + s_1) \), for appropriate \( C_7 \).
In order to consider the behavior of $X^H(\cdot)$ on $B^c_{s_1,k}$, we find it convenient to employ the service time distribution $F^{s_1}(\cdot)$ that is given by

\[
F^{s_1}(s) = \begin{cases} 
F(s) & \text{for } s < s_1, \\
1 & \text{for } s \geq s_1.
\end{cases}
\]

We define $X^H_{s_1}(\cdot)$ analogously to $X^H(\cdot)$, but where the service time distribution of the process is $F^{s_1}(\cdot)$ up to and including the service time interval containing $\tau_k$, and is given by $F(\cdot)$ afterwards; $Z^H_{s_1}(\cdot)$ and $S^H_{s_1}(\cdot)$ are defined analogously. One has

\[
E[V_k; B^c_{s_1,k}] \leq E[V^{s_1}_k],
\]

where $V^{s_1}_k$ is the occupation time at states $x$ with $z \geq k$ for $X^H_{s_1}(\cdot)$. Note that the mean of $F^{s_1}(\cdot)$ is at most 1.

In contrast to Proposition 4.3, Proposition 4.4 requires us to restrict our choice of $s_1$ in terms of $k$. For this, we set $k_1 = \lfloor k/3 \rfloor$ and introduce the abbreviation

\[
p = p_{k_1} = \alpha D P_{k_1}^{D-1}.
\]

The required restriction on $s_1$ is that

\[
s_1 \leq k^{1-\eta}/p,
\]

where $\eta \in (0, 1/2)$. In the proof of Proposition 4.2, we will introduce an iterative scheme that involves explicit choices of $s_1$ based on our knowledge of $P_{k_1}$ at each step.

Proposition 4.4 gives us the following upper bound for $E[V_k; B^c_{s_1,k}]$.

**Proposition 4.4.** Consider a family of JSQ networks with the same assumptions holding as in Proposition 4.2. Suppose that $\delta > 0$ and $\eta \in (0, 1/2)$ are given, and that $s_1$ satisfies (4.11) Then, for appropriate $C_9$ and all $k$,

\[
E[V_k; B^c_{s_1,k}] \leq C_9(k + s_1) \exp\{-\delta k^\eta\}.
\]

The demonstration of Proposition 4.4 depends on an appropriate supermartingale. In order to construct the supermartingale, we employ the following notation. We fix $k_0 \in \mathbb{Z}_+$, which will not depend on $k$ as $k$ increases, and set $k_2 = 2k_1$, where $k_1$ is as defined earlier. We set

\[
f(z) = (z \wedge k_2) - N_1 \exp\{-\theta(z \wedge k_0)\} + \gamma^{-1} \exp\{\phi(z \vee k_2)\} - \gamma^{-1} \exp\{\phi k_2\},
\]
where \( N_1, \theta > 0, \phi = \delta k^{n-1} \) and \( \gamma = \phi e^{\delta k^2} \), and where \( \delta > 0 \) and \( \eta \in (0, 1/2) \) are as in Proposition 4.4; the function \( f(\cdot) \) is sketched in Figure 1. The terms \( P_k \) will continue to refer to the probabilities defined at the beginning of the paper with respect to the cavity process with the original service distribution \( F(\cdot) \) (not \( F^{s_1}(\cdot) \)).

We let \( H(n) \), with \( n \geq 1 \), denote the number of jobs for the process \( X^H_{s_1}(\cdot) \), with \( X^H_{s_1}(0) = 0 \), at the time when the \( n \)th job has just departed; we set \( H(0) = 1 \), and we let \( \rho \) denote the first time \( n \) at which either \( H(n) = 0 \) or \( H(n) \geq k - 1 \). Using this notation, we define the analog of \( M(\cdot) \) in (3.26),

\[
M(n) = f(H(n \wedge \rho)).
\]

Note that, unlike for \( M(\cdot) \) in (3.26), \( M(\cdot) \) here depends strongly on the choice of \( k \). Also, unlike \( M(\cdot) \) in (3.26), it was not necessary to wait until the first departure in defining \( H(0) \), since \( X^H_{s_1}(0) = 0 \), and hence there is no initial residual service time; in both cases, \( H(1) - H(0) \) is the change in the number of jobs during the service time of the first job that begins service when \( t > 0 \).

**Proposition 4.5.** Consider a family of JSQ networks with the same assumptions holding as in Proposition 4.2. Suppose that \( \delta > 0 \) and \( \eta \in (0, 1/2) \) are given, and that \( M(\cdot) \) is defined as above. Also, assume that \( s_1 \) satisfies (4.11). Then, for large enough \( k \), \( M(\cdot) \) is a supermartingale, with respect to the filtration \( \mathcal{G}_n = \sigma(H(0), \ldots, H(n)) \), for small enough \( \delta > 0 \), and appropriate \( \theta, N_1 > 0 \), with \( \delta, \theta \), and \( N_1 \) not depending on \( k \).
The demonstration of Proposition 4.5 will be given at the end of the section. Employing Proposition 4.5, we now demonstrate Proposition 4.4.

**Proof of Proposition 4.4.** We suppose that the terms $\delta$, $\theta$ and $N_1$ are chosen so that, for large enough $k$, $M(\cdot)$ is a supermartingale. Set $\sigma_L = \min\{n : M(n) \geq L\}$, for given $L > 0$, which will depend on $k$. Since $M(\cdot)$ is bounded below by $-N_1$ and $M(0) \leq 1$, by the optional sampling theorem,

\[ P(\sigma_L < \infty) \leq \frac{1}{L}(1 + N_1). \tag{4.15} \]

On the other hand, denoting by $n_k$ the service interval during which $Z^H_{s_1}(t) = k$ first occurs and by $T_{n_k}$ the end of that interval, $H(n_k) = Z^H_{s_1}(T_{n_k}) \geq k - 1$. Substituting this into (4.13)-(4.14) and recalling that $\phi = \delta k^{-\gamma} - 1$, one obtains

\[ M(n_k) \geq -N_1 + \gamma^{-1}\exp\{\phi(k-1)\} - \gamma^{-1}\exp\{2\phi k/3\} \geq \exp\{\delta k^{-\gamma}\}/2\gamma, \]

for large $k$. Let $\tau^s_k$ denote the first time $t$, during the first cycle, at which $Z^H_{s_1}(t) = k$. Plugging $L = \exp\{\delta k^{-\gamma}\}/2\gamma$ into (4.15), substituting in for $\gamma$ and recalling that $k_2 = 2[k/3]$, it follows that, for large $k$,

\[ P(\tau^s_k < \infty) \leq P(\sigma_L < \infty) \leq \exp\{-\delta k^{-\gamma}\} \cdot \exp\{2\delta k^{-\gamma}/3\} = \exp\{-\delta k^{-\gamma}/3\}. \tag{4.16} \]

Lemma 3.1 applied to $F(\cdot)$, which is the service distribution of new service times after $\tau^s_k$, provides the upper bound

\[ E[V^s_{k} | \mathcal{F}_{\tau^s_k}] \leq 2(k + s + N_0), \]

given that $S^H_{s_1}(\tau^s_k) = s$. Since the residual service time for $X^H_{s_1}(t)$ is at most $s_1$ for $t \leq \tau^s_k$, it therefore follows from (4.16) that, for large $k$,

\[ E[V^s_{k}] \leq 3(k + s_1) \exp\{-\delta k^{-\gamma}/3\}. \tag{4.17} \]

The inequality in (4.12) follows upon applying (4.9) to (4.17) and substituting in a smaller choice of $\eta$. \[ \square \]

We combine the upper bounds given in Propositions 4.3 and 4.4 for $E[V_k; B_{s_1}]$ and $E[V_k; B_{s_1}^c]$ to obtain the following upper bound on $E[V_k]$. Since we will always assume $s_1 \leq k^{\nu_{\beta_1} + 1}$ in our application of the corollary, this allows us to omit the exponential term inherited from (4.12).
Corollary 4.1. Consider a family of JSQ networks with the same assumptions holding as in Proposition 4.2. Fix \( \eta \in (0, 1) \) and assume that

\[
s_1 \leq \left[ (\alpha D)^{-1} k^{1-\eta} P_{-1}^{1-D} \right] \land k^N,
\]

for some \( N > 0 \). Then, for appropriate \( C_{10} \) and all \( k \),

\[
E[V_k] \leq C_{10} s_1^{-\beta} (k + s_1).
\]

Proof. It follows from Propositions 4.3 and 4.4 that

\[
E[V_k] \leq C_7 s_1^{-\beta} (k + s_1) + C_9 (k + s_1) \exp\{-\delta k^n\}
\]

for appropriate \( C_7 \) and \( C_9 \). The assumption \( s_1 \leq k^N \) allows us to absorb the second term into the first.

The following elementary lemma will be employed in the proof of Proposition 4.2.

Lemma 4.1. Suppose that \( R(n) \) satisfies

\[
R(n) = aR(n-1) + b \quad \text{for } n \geq 1,
\]

with \( R(0) = c \), for \( a \in (0, 1) \) and \( b, c \in \mathbb{R} \). Then,

\[
\lim_{n \to \infty} R(n) = b/(1 - a).
\]

If \( R(0) < b/(1 - a) \), then the sequence \( R(n) \) is increasing, and if \( R(0) > b/(1 - a) \), then the sequence is decreasing.

Proof. Setting \( \tilde{R}(n) = R(n) - b/(1 - a) \), it follows from (4.20) that

\[
\tilde{R}(n) = a\tilde{R}(n-1) \quad \text{for } n \geq 1,
\]

with \( \tilde{R}(0) = c - b/(1 - a) \). All of the claims follow by iterating (4.22).

We will employ the lemma in the following multiplicative format.

Corollary 4.2. Suppose that \( Q_k(n) \) satisfies

\[
Q_k(n) = \left( k^{-(1-2\eta)} Q_k(n-1)^{D-1} \right)^{\beta-1} \quad \text{for } n \geq 1,
\]
with $Q_k(0) = k^{1 - \beta + 2\eta\beta}$, for $(D - 1)(\beta - 1) \in (0, 1)$ and $\eta \in (0, 1/2)$. Then, $Q_k(n)$ satisfies $Q_k(n) = k^{-R(n)}$, where the sequence $R(n)$ is increasing in $n$ and

\begin{equation}
\lim_{n \to \infty} R(n) = (1 - 2\eta)\nu_\beta,
\end{equation}

with $\nu_\beta = (\beta - 1)/[1 - (D - 1)(\beta - 1)]$.

**Proof.** The limit in (4.24) follows from (4.21) upon setting $a = (D - 1)(\beta - 1)$, $b = (1 - 2\eta)(\beta - 1)$ and $c = \beta - 1 - 2\eta\beta$. The sequence $R(n)$ is increasing since $R(0) < (1 - 2\eta)\nu_\beta$. \qed

We now employ Corollaries 4.1 and 4.2 to demonstrate Proposition 4.2.

**Proof of Proposition 4.2.** For given $k$ and $\eta \in (0, 1/2)$, we define $Q_k(n)$ as in Corollary 4.2 and set

\begin{equation}
s_1(n) = (\alpha D)^{-1}k^{1-\eta}
\end{equation}

for $n = 0$,

\begin{equation}
= (\alpha DQ_{k_1}(n - 1)^2 - 1)^{-1}k^{1-\eta}
\end{equation}

for $n \geq 1$,

where $k_1 = \lfloor k/3 \rfloor$. Using $s_1(n)$, we will inductively show that, for large $k$ (depending on $\eta$),

\begin{equation}
P_k \leq Q_k(n)
\end{equation}

for all $n \geq 0$.

Letting $n \to \infty$, it therefore follows from the corollary that

\begin{equation}
P_k \leq k^{-(1 - 2\eta)\nu_\beta}.
\end{equation}

This implies (4.4) in Proposition 4.2, with $\delta < 2\eta$.

To show (4.26) holds for $n = 0$, we note that $s_1(0)$ satisfies (4.18). Therefore, by (2.4) and Corollary 4.1, for large $k$,

\begin{equation}
P_k \leq 2C_{10}(m_0)^{-1}s_1(0)^{-\beta}k \leq k^{-(\beta - 1) + 2\eta\beta} = Q_k(0),
\end{equation}

where the constants in the second expression are absorbed in the third expression by using the $2\eta$ term. Note that, in this application of (4.19), $s_1(0) \leq k$. In the application of (4.19) given next, $s_1(n) \geq k$ for all $n \geq 1$.

Suppose that (4.26) holds with $n - 1$ in place of $n$. Choosing $s_1(n)$ as in (4.25) and employing the lower bound for $Q_k(n)$ given in (4.24), one can check that $s_1(n)$ satisfies (4.18), with $N = \nu_\beta + 1$. Also note that, by Corollary 4.2,

\begin{equation}
Q_{k_1}(n) \leq 3^{\nu_\beta}Q_k(n)
\end{equation}
for large $k$ and all $n$. Applying (2.4) and Corollary 4.1 again, we therefore obtain that, for large $k$,

$$P_k \leq 2C_{10}(m_0)^{-1}s_1(n)^{-\beta - 1} \leq \left( k^{-(1-2\eta)}Q_k(n-1)^{D-1} \right)^{\beta - 1} = Q_k(n).$$

This demonstrates (4.26).

In order to complete the demonstration of Proposition 4.2, we need to prove Proposition 4.5, which asserts that $M(\cdot)$, given by (4.14), is a supermartingale.

**Proof of Proposition 4.5.** We need to show the supermartingale inequality (3.27) for $H(n) \in (0, k - 1)$. We do this separately over the intervals $(0, k_1]$ and $(k_1, k - 1)$. The basic idea for the first interval will be to show that, on $(0, k_1]$, (3.27) will be satisfied for the same reasons as was $M(\cdot)$, for $M(\cdot)$ given by (3.26), the point being that, since $k_2 - k_1 = \lfloor k/3 \rfloor$ is large, the role played by the additional terms $\gamma^{-1}\exp\{\phi(z \lor k_2)\} - \gamma^{-1}\exp\{\phi k_2\}$ in (4.13) is negligible. On the second interval $(k_1, k - 1)$, the strong negative drift of $Z_{H}^{H_1}(\cdot)$ will be enough to compensate for both the $z \lor k_2$ and $\gamma^{-1}\exp\{\phi(z \lor k_2)\} - \gamma^{-1}\exp\{\phi k_2\}$ terms. We do the latter interval first.

We claim that for large $k$ and $H(n) \geq k_1$,

$$E[\exp\{\phi H(n + 1)\} \mid G_n] \leq E[\exp\{\phi H(n)\}].$$

We first note that, because of (4.10), for $H(n) \geq k_1$, the number of arrivals over the $(n + 1)$st service interval is dominated by a mixture of Poisson rate-$ps$ random variables, with $s$ being distributed according to $F^{s_1}(\cdot)$. Therefore,

$$E[\exp\{\phi(H(n + 1) - H(n))\} \mid G_n] \leq e^{-\phi} \int_0^{s_1} \exp\{ps(e^\phi - 1)\} F^{s_1}(ds).$$

Since the integrand is convex and the mean of $F^{s_1}(\cdot)$ is at most 1, the right hand side is at most

$$e^{-\phi} \left[ \left( 1 - \frac{1}{s_1} \right) + \frac{1}{s_1} \exp\{ps_1(e^\phi - 1)\} \right].$$

On account of the definitions of $\phi$ and $p$ given between (4.10) and (4.14), both $\phi$ and $ps_1 \phi$ are at most $\delta$. Using $e^z \sim 1 + z$ for $z$ close to 0, one can therefore check that, for given $\epsilon > 0$ and small enough $\delta > 0$, (4.31) is at most

$$1 + \phi[(1 + \epsilon)p - (1 - \epsilon)].$$
For \( p \leq (1 - \epsilon)/(1 + \epsilon) \), the above quantity is at most 1, which holds here since \( p \to 0 \) as \( k \to \infty \). This implies (4.30).

For \( H(n) > k_2 \), it is easy to see that (3.27) follows from (4.30), since

\[
(4.32) \quad f(z) - \gamma^{-1} e^{\phi z} = b \quad \text{for } z \geq k_2, \\
\leq b \quad \text{for } z < k_2,
\]

where \( b \overset{\text{def}}{=} f(k_2) - \gamma^{-1} e^{\phi k_2} \). For \( H(n) \in (k_1, k_2] \), (3.27) follows from (4.30) with a bit more work. In place of (4.32), one uses

\[
(4.33) \quad g(z) \overset{\text{def}}{=} f(z) - \gamma' e^{\phi z} \leq f(H(n)) - \gamma' e^{\phi H(n)}
\]

for all \( z \), where \( \gamma' \overset{\text{def}}{=} (\phi e^{\phi H(n)})^{-1} - \gamma^{-1} e^{\phi(k_2-H(n))} \). To check (4.33), note that equality holds for \( z = H(n) \); we claim that the maximum of \( g(\cdot) \) is taken there. One has \( g'(H(n)) = 0 \) because of our definition of \( \gamma' \); \( g'(z) \geq 0 \) for \( z \leq H(n) \) and \( g'(z) \leq 0 \) for \( z \in [H(n), k_2) \) because of the concavity of \( g(\cdot) \) there; and since \( \gamma' \geq 1 \), for \( z > k_2 \), it is easy to see that \( g'(z) \leq 0 \) there. This shows (4.33) and hence (3.27) for \( H(n) \in (k_1, k_2] \) as well.

We still need to show (3.27) for \( H(n) \in (0, k_1] \). For this, we compare \( M(\cdot) \) with \( \tilde{M}(\cdot) \), where

\[
\tilde{f}(z) = z + n/2 - N_1 \exp\{-\theta(z \wedge k_0)\}
\]

and

\[
\tilde{M}(n) = \tilde{f}(H(n \wedge \rho)).
\]

Set \( R(n) = M(n) - \tilde{M}(n) \). For \( H(n) \in (0, k_1] \), one has

\[
(4.34) \quad R(n + 1) - R(n) + 1/2 = 0 \quad \text{for } H(n + 1) \leq k_2, \\
\leq \gamma^{-1} e^{\phi H(n + 1)} \quad \text{for } H(n + 1) > k_2.
\]

Since \( \tilde{M}(\cdot) \) is the supermartingale in (3.26), except with a different initial state, \( \tilde{M}(\cdot) \) satisfies (3.27) if \( \theta \) and \( N_1 \) are chosen as in (3.26). In a moment, we will show that

\[
(4.35) \quad E[e^{\phi H(n + 1)} \mathbf{1}\{H(n + 1) > k_2\} | \mathcal{G}_n] \leq \gamma/2
\]

for \( H(n) \leq k_1 \) and large \( k \). Using (4.34) and (4.35), (3.27) therefore also follows for \( M(\cdot) \) for \( H(n) \leq k_1 \).

It suffices to show (4.35) for \( H(n) = k_1 \). To do this, we need to control the right tail of \( H(n + 1) \). The number of arrivals over the \((n+1)\)st service interval for the cavity process is dominated by a mixture of Poisson mean-\( ps_1 \) random
variables, with the mixture distributed according to $F_{s_1}$. This mixture is in turn dominated by a Poisson mean-$s_1$ random variable. Therefore, the left hand side of (4.35) is at most

\begin{equation}
\sum_{k' = k_2}^{\infty} \left[ e^{-ps_1}(ps_1)^{k' - k_1}/(k' - k_1)! \right] e^{\phi k'}.
\end{equation}

Setting $\ell = k' - k_2$, one has

\[(k' - k_1)! \geq \ell!(k_2 - k_1)! \geq \ell!((k_2 - k_1)/e)^{k_2 - k_1},\]

where the last inequality follows from Stirling’s formula. Substituting $\ell$ into (4.36), applying this bound, and employing \(\exp\{e^\phi ps_1\} = \sum_\ell^\infty (e^\phi ps_1)^\ell/\ell!\), it follows that (4.36) is at most

\begin{equation}
\left( \frac{e^{ps_1}}{k_2 - k_1} \right)^{k_2 - k_1} \exp \left\{ ps_1(e^\phi - 1) + \phi k_2 \right\} \leq C_{11} k^{-\eta k/3} e^{4\phi k}
\end{equation}

for appropriate $C_{11}$, where the inequality employs (4.11) and $e^\phi - 1 \leq 2\phi$, for small $\phi$. As $k \to \infty$, the right hand side of (4.37) goes to 0. It follows that the left hand side of (4.35), with $H(n) = k_1$, goes to 0 as $k \to \infty$. This implies (4.35) holds for $H(n) \leq k_1$ and large $k$, which completes the proof of the proposition.

5. **The case where $\beta = D/(D - 1)$**. In this section, we demonstrate Theorem 1.3. We do this by demonstrating the lower and upper bounds needed for the theorem, in Propositions 5.1 and 5.2.

**Proposition 5.1.** Consider a family of JSQ networks, with given $D \geq 2$ and $N = D, D + 1, \ldots$, where the $N$th network has Poisson rate-$\alpha N$ input, with $\alpha < 1$, and where service at each queue is FIFO, with distribution $F(\cdot)$ having mean 1. Assume that (1.2) holds and that

\begin{equation}
\bar{F}(s) \geq c_1 s^{-D/(D-1)} \quad \text{for } s \geq s_0,
\end{equation}

for some $c_1 > 0$ and $s_0 \geq 1$. Then, for appropriate $C_{12} > 0$ and $s_D(c_1) < \infty$,

\begin{equation}
P_k \geq C_{12} e^{-s_D(c_1)k} \quad \text{for all } k,
\end{equation}

where

\begin{equation}
s_D(c_1) \searrow 0 \quad \text{as } c_1 \nearrow \infty,
\end{equation}

\begin{equation}
\sum_{k' \geq \ell} \left[ e^{-ps_1}(ps_1)^{k' - k_1}/(k' - k_1)! \right] e^{\phi k'}.
\end{equation}

Setting $\ell = k' - k_2$, one has

\[(k' - k_1)! \geq \ell!(k_2 - k_1)! \geq \ell!((k_2 - k_1)/e)^{k_2 - k_1},\]

where the last inequality follows from Stirling’s formula. Substituting $\ell$ into (4.36), applying this bound, and employing \(\exp\{e^\phi ps_1\} = \sum_\ell^\infty (e^\phi ps_1)^\ell/\ell!\), it follows that (4.36) is at most

\begin{equation}
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\end{equation}

for appropriate $C_{11}$, where the inequality employs (4.11) and $e^\phi - 1 \leq 2\phi$, for small $\phi$. As $k \to \infty$, the right hand side of (4.37) goes to 0. It follows that the left hand side of (4.35), with $H(n) = k_1$, goes to 0 as $k \to \infty$. This implies (4.35) holds for $H(n) \leq k_1$ and large $k$, which completes the proof of the proposition.

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\begin{equation}
\bar{F}(s) \geq c_1 s^{-D/(D-1)} \quad \text{for } s \geq s_0,
\end{equation}

for some $c_1 > 0$ and $s_0 \geq 1$. Then, for appropriate $C_{12} > 0$ and $s_D(c_1) < \infty$,

\begin{equation}
P_k \geq C_{12} e^{-s_D(c_1)k} \quad \text{for all } k,
\end{equation}

where

\begin{equation}
s_D(c_1) \searrow 0 \quad \text{as } c_1 \nearrow \infty,
\end{equation}

\begin{equation}
\sum_{k' \geq \ell} \left[ e^{-ps_1}(ps_1)^{k' - k_1}/(k' - k_1)! \right] e^{\phi k'}.
\end{equation}

Setting $\ell = k' - k_2$, one has

\[(k' - k_1)! \geq \ell!(k_2 - k_1)! \geq \ell!((k_2 - k_1)/e)^{k_2 - k_1},\]

where the last inequality follows from Stirling’s formula. Substituting $\ell$ into (4.36), applying this bound, and employing \(\exp\{e^\phi ps_1\} = \sum_\ell^\infty (e^\phi ps_1)^\ell/\ell!\), it follows that (4.36) is at most

\begin{equation}
\left( \frac{e^{ps_1}}{k_2 - k_1} \right)^{k_2 - k_1} \exp \left\{ ps_1(e^\phi - 1) + \phi k_2 \right\} \leq C_{11} k^{-\eta k/3} e^{4\phi k}
\end{equation}

for appropriate $C_{11}$, where the inequality employs (4.11) and $e^\phi - 1 \leq 2\phi$, for small $\phi$. As $k \to \infty$, the right hand side of (4.37) goes to 0. It follows that the left hand side of (4.35), with $H(n) = k_1$, goes to 0 as $k \to \infty$. This implies (4.35) holds for $H(n) \leq k_1$ and large $k$, which completes the proof of the proposition.

5. **The case where $\beta = D/(D - 1)$**. In this section, we demonstrate Theorem 1.3. We do this by demonstrating the lower and upper bounds needed for the theorem, in Propositions 5.1 and 5.2.

**Proposition 5.1.** Consider a family of JSQ networks, with given $D \geq 2$ and $N = D, D + 1, \ldots$, where the $N$th network has Poisson rate-$\alpha N$ input, with $\alpha < 1$, and where service at each queue is FIFO, with distribution $F(\cdot)$ having mean 1. Assume that (1.2) holds and that

\begin{equation}
\bar{F}(s) \geq c_1 s^{-D/(D-1)} \quad \text{for } s \geq s_0,
\end{equation}

for some $c_1 > 0$ and $s_0 \geq 1$. Then, for appropriate $C_{12} > 0$ and $s_D(c_1) < \infty$,

\begin{equation}
P_k \geq C_{12} e^{-s_D(c_1)k} \quad \text{for all } k,
\end{equation}

where

\begin{equation}
s_D(c_1) \searrow 0 \quad \text{as } c_1 \nearrow \infty,
\end{equation}
Proposition 5.2. Consider a family of JSQ networks, with given $D \geq 2$ and $N = D, D+1, \ldots$, where the $N$th network has Poisson rate-$\alpha N$ input, with $\alpha < 1$, and where service at each queue is FIFO, with distribution $F(\cdot)$ having mean 1. Assume that (1.2) holds and that

$$\bar{F}(s) \leq c_2 s^{-D/(D-1)} \quad \text{for} \quad s \geq s_0,$$

for some $c_2 < \infty$ and $s_0 \geq 1$. Then, for appropriate $C_{13}$ and $r_D(c_2) > 0$,

$$P_k \leq C_{13} e^{-r_D(c_2)k} \quad \text{for all} \quad k,$$

where

$$r_D(c_2) \nearrow \infty \quad \text{as} \quad c_2 \searrow 0.$$

Theorem 1.3 follows immediately from Propositions 5.1 and 5.2.

As in the previous two sections, the demonstration of the lower bound is substantially quicker than that of the upper bound. We first demonstrate the lower bound, Proposition 5.1 and then, in the remainder of the section, derive the upper bound Proposition 5.2.

Demonstration of Proposition 5.1. As in Sections 3 and 4, where we considered the cases $\beta > D/(D-1)$ and $\beta \in (1, D/(D-1))$, for the lower bound, it suffices to construct a path along which $Z^H(t)$ increases from 0 to $k$ within the first cycle. In contrast to the previous two settings, we allocate geometrically increasing amounts of time to the sequence of arrivals, up through the $k$th arrival; as before, these arrivals are required to occur before the time of the first departure.

Proof of Proposition 5.1. The argument is similar to that for Proposition 4.1 in that we examine the cavity process $X^H(\cdot)$ with $X^H(0) = 0$, and obtain a lower bound on the expected amount of time $V_k$ over which $Z^H(t) \geq k$ before $X^H(\cdot)$ returns to 0. Here, we argue by induction, and assume that

$$P_i \geq C_{12} e^{-a_1 i} \quad \text{for} \quad i = 0, \ldots, k-1,$$

for given $k$, where $C_{12} \leq [(a_1 \lor 1)s_0]^{-1}$, and $a_1 > 0$ will be specified later.

We consider the following event $A$ that leads to a lower bound on $P_k$ that is compatible with (5.7). We stipulate that the first service time is at least

$$s_1 \overset{\text{def}}{=} C_{14} e^{a_1(D-1)k},$$
where \( C_{14} = 4(\alpha a_1)^{-1}C_{12}^{-(D-1)} \). Note that \( C_{14} \geq s_0 \). We also assume that the interarrival time for the \((i + 1)\)st arrival at the queue, \( i = 0, \ldots, k - 1 \), is at most

\[
(5.9) \quad \alpha^{-1}C_{12}^{-(D-1)} \exp\{\frac{1}{2}a_1(D-1)(k+i)\}.
\]

A little estimation shows that the sum of the terms in (5.9), over \( i = 0, \ldots, k - 1 \), is bounded above by

\[
(5.10) \quad \alpha^{-1}C_{12}^{-(D-1)} \exp\{a_1(D-1)k\}/(\exp\{\frac{1}{2}a_1(D-1)\} - 1) \leq (2/\alpha a_1)C_{12}^{-(D-1)} \exp\{a_1(D-1)k\},
\]

which is one-half of (5.8).

On account of the induction hypothesis in (5.7), the probability that the \((i + 1)\)st arrival occurs within the interarrival time in (5.9) is at least

\[
1 - \exp\{-\frac{1}{2}a_1(D-1)(k-i)\}.
\]

So, the probability that the corresponding events for \( i = 0, \ldots, D - 1 \) all occur within the allotted time is at least

\[
\prod_{i=1}^{k} \left(1 - \exp\{-\frac{1}{2}a_1(D-1)i\}\right) \geq \psi(a_1),
\]

where \( \psi(a_1) > 0 \) for \( a_1 > 0 \) and does not depend on \( k \) or \( D \), with \( \psi(a_1) \to 1 \) as \( a_1 \to \infty \); the inequality requires a little computation.

It follows from the previous two paragraphs that the event \( A \), given by the service time and interarrival times restricted as in (5.8) and (5.9), has probability at least

\[
\psi(a_1)\bar{F}(C_{14} \exp\{a_1(D-1)k\}).
\]

On \( A \), \( Z^H(t) \geq k \) over the interval \([s_1/2, s_1]\), which has length \( \frac{1}{2}C_{14} \exp\{a_1(D-1)k\} \). So,

\[
E[V_k] \geq \frac{1}{2}C_{14} \psi(a_1) \exp\{a_1(D-1)k\} \bar{F}(C_{14} \exp\{a_1(D-1)k\}).
\]

By substituting the bound in (5.1) for \( \bar{F}(s) \) and employing \( P_k = m_0^{-1}E[V_k] \), one obtains

\[
P_k \geq \frac{1}{2m_0} \psi(a_1)c_1C_{14} \exp\{a_1(D-1)k\}(C_{14} \exp\{a_1(D-1)k\})^{-D/(D-1)}
\]

\[
= \frac{1}{2m_0} \psi(a_1)c_1(C_{14})^{-1/(D-1)}e^{-a_1k} \geq \frac{c_1}{4m_0} \psi(a_1)(\alpha a_1)^{1/(D-1)}C_{12} e^{-a_1k}.
\]
For given \( c_1 \) and large enough \( a_1 \), the last quantity in the above display is at least \( C_{12}e^{-a_1k} \). This implies the induction hypothesis in (5.7) for \( k \) and this choice of \( a_1 \). Since (5.7) obviously holds for \( i = 0 \), (5.2) follows, with \( s_D(c_1) = a_1 \). Similarly, for given \( a_1 \), one obtains the lower bound \( C_{12}e^{-a_1k} \), if \( c_1 \) is chosen large enough, which implies (5.3). This completes the proof. □

Demonstration of Proposition 5.2. The demonstration of the upper bound (5.5) is substantially more involved than is the lower bound. The basic idea is similar to that employed for the upper bound in Section 3, where we classified different paths for attaining \( Z^H(t) + k \), for given \( k \) and some \( t \), in terms of partitions \( \pi \) given by (3.31). There, the probability of the event associated with the trivial partition dominated the probabilities for the other partitions. Computing an upper bound for the probability for the trivial partition and multiplying by the upper bound \( 2^\beta \) for the total number of partitions gave us our desired upper bounds on \( P_k \).

The details of our setup here will be different. The partitions we consider will be defined somewhat differently, and we will need to be more careful in summing up probabilities – we will compute the probability of the event associated with the trivial partition separately, and will then sum up the probabilities for the other partitions, which will be negligible in comparison. We will also require an upper bound on \( P_k \) from Proposition 4.2, at the beginning of our argument. On the other hand, the computations of these upper bounds will be substantially easier here than the corresponding bounds were in Section 3. The key difference is that here the probabilities \( P_k \) will decrease sufficiently slowly in \( k \) so that, for our estimates, not too much will be lost if we consider \( P_i \) to be approximately the same for \( i = k_1, \ldots, k-1 \), which will simplify our computations.

In order to show (5.5) and (5.6) of Proposition 5.2, we will argue by induction, assuming that, for preassigned \( a_2, C_{13} > 0 \) and \( k_0, h_T \in \mathbb{Z}_+ \),

\[
(5.11) \quad P_i \leq C_{13}e^{-a_2i} \quad \text{for } i = k_0, \ldots, k-1,
\]

for given \( k \) with \( k \geq k_0 + h_T \). For appropriate choices of these preassigned values, we will show that the inequality in (5.11) holds with \( i = k \). We set

\[
(5.12) \quad h_T = \lceil 700D^2c_2 \rceil^{D-1} \vee 6
\]

and

\[
(5.13) \quad a_2 = (h_T)^{-1} \vee \frac{1}{6} \log \left( (220D^2c_2)^{-1} \right),
\]

where \( c_2 \) is as in (5.4). These particular choices of \( h_T \) and \( a_2 \) are not needed for most of the argument, and will only be inserted at the very end.
In order to specify $C_{13}$ and $k_0$, we note that, since (4.3) is satisfied for every $\beta < D/(D-1)$ because of (5.4) and since $\nu_\beta \nearrow \infty$ as $\beta \nearrow D/(D-1)$, it follows from Proposition 4.2 that, for any $N$, $\lim_{k \to \infty} k^N P_k = 0$. Here, we set $N = h_T + 1$. We choose $k_0$ large enough so that $P_{k_0} \leq (DM^2 k_0^N)^{-1}$, $(1 + 1/k_0)^N \leq e^{q_2}$,

(5.14) \[ k_0 \geq D(c_2 \vee (1/c_2))s_0^{2h_T} e^{h_T+1} \]

and $k_0 \geq N_0$ all hold, where $M = e^{q_2 h_T}$, $s_0$ is as in (5.4) and $N_0$ is as in Lemma 3.1. Setting $C_{13} = Me^{q_2 k_0} P_{k_0}$ implies (5.11) holds for $k = k_0, \ldots, k_0 + h_T$, which we will need in order to begin our induction argument.

It follows from the definition of $C_{13}$ and the first two conditions on $k_0$ that

\[ C_{13} DMe^{-q_2 k} \leq k^{-N} \]

for all $k \geq k_0$.

Setting $q_k = \alpha D (C_{13} Me^{-q_2 k})^{D-1}$, it follows from this that

(5.15) \[ q_k \leq k^{-(D-1)N} \]

for all $k \geq k_0$,

which we will use throughout the induction argument for (5.11). In order to follow the basic induction argument, the reader should keep in mind (5.11) and (5.15), without worrying much about the other inequalities.

In order to demonstrate the inequality in (5.11) with $i = k$, we proceed as outlined in the beginning of the subsection, employing the partitions $\pi$ given in (3.31) and the events $A_\pi$, on which a sequence of arrivals and departures occurs in the first cycle that induces the partition $\pi$. We define $\Pi_k$, as before, as the set of all partitions with final element $i_m = k$; here, the first element will be $i_0 + 1$, with $i_0 = k_1$, where $k_1 = k - h_T$. In the present setting, we will pay more attention than in Section 3 to the length of each of the sets in a partition $\pi$, setting $h_\ell = |G_\ell|$, for $\ell = 1, \ldots, m_\pi$, for the number of elements in the $\ell$th set $G_\ell$ of the partition; one has $h_T = \sum_{\ell=1}^{m_\pi} h_\ell$.

An important step in computing an upper bound for $P_k$ is Proposition 5.3, which is the analog of Proposition 3.4. Rather than employing $L_\ell(s)$ as in the proof of Proposition 3.4 for the upper bound for a set in the partition, we employ

(5.16) \[ J_{k,h}(s) \equiv e^{-q_k s} \sum_{i=h}^{\infty} (q_k s)^i / i! \]

The quantity $J_{k,h}(s)$ is the probability of at least $h$ events occurring for a mean-$q_k(s)$ Poisson random variable, and dominates the probability that,
over the time interval \((0, s]\), at least \(h\) arrivals occur for a cavity process \(X^H(\cdot)\) with \(Z^H(0) \geq h\) and \(S^H(0) \geq s\). This bound follows from the upper bound in (2.5), together with the induction hypothesis (5.11) and our definition of \(M\).

**Proposition 5.3.** Consider a family of JSQ networks with the same assumptions holding as in Proposition 5.2, except that (5.4) is not assumed. Suppose that the induction assumption (5.11) holds for given \(h_T\) and for \(k_0 \geq N_0\), where \(N_0\) is as in Lemma 3.1. Then,

\[
P_k \leq 3 \sum_{\pi \in \Pi_k} (3k)^{m_\pi - 1} \prod_{\ell = 1}^{m_\pi - 1} \left( \int_0^\infty J_{k,h_\ell}(s) F(ds) \right) \times \int_0^\infty (k + s) J_{k,h_{m_\pi}}(s) F(ds).
\]

**Proof.** One can reason similarly to the argument for (3.36), in the proof of Proposition 3.4, by computing an upper bound on \(E[V_k; A_{\pi}]\). Summation over \(\pi \in \Pi_k\) and application of (2.4) will then imply (5.17). The assumption \(k_0 \geq N_0\) is needed only to absorb the term \(N_0\) when applying Lemma 3.1.

One argues inductively, repeating the argument for (3.36), except for the substitution of \(J_{k,h_\ell}(s)\) for \(L_\ell(s)\) and a minor change involving the factors of \(3k\). For each step with \(\ell < m_\pi\), one obtains an additional factor \(i_{\ell-1}^* \int_0^\infty J_{k,h_\ell}(s) F(ds)\) and, for \(\ell = m_\pi\), one obtains the factor \(3i_{m_\pi-1}^* \int_0^\infty (k + s) J_{k,h_{m_\pi}}(s) F(ds)\), where \(i_{\ell-1}^* = 3i_{\ell-1}\) for \(\ell \geq 2\) and \(i_0^* = m_0\), with \(m_0\) being the mean return time to 0 for \(X^H(\cdot)\). For \(\ell < m_\pi\), the integral part of the factor is obtained by employing the comparison given directly before the statement of the proposition, comparing \(J_{k,h_\ell}(s)\) with the probability of at least \(h\) arrivals over a service time of at least \(s\), and then by integrating against \(s\); for \(\ell = m_\pi\), one also employs (3.24) to provide an upper bound on the expected occupation time \(V_k\).

For \(\ell \geq 2\), the factor \(i_{\ell-1}^*\) is obtained by applying (3.25), with \(s = 0\), which gives an upper bound on the expected number of service intervals occurring over the remainder of the cycle, after the service interval corresponding to the \((\ell - 1)st\) step ends. For \(\ell_0\), instead of the factor \(3i_0\), one can employ \(m_0\), since this is the expected number of service intervals over an entire cycle, and no conditioning is needed for this first step. Since each of the remaining factors is at most \(3k\), the product of all of the factors is at most \(m_0(3k)^{m_\pi - 1}\), and since \(P_k = (m_0)^{-1} E[V_k]\), the \(m_0\) factors cancel, and one obtains the \((3k)^{m_\pi - 1}\) factor in (5.17). (The improved bound just obtained by removing a factor of \(3k\) will only be needed when bounding the right hand side of (5.17) for the trivial partition, in Proposition 5.4.)
In Propositions 5.4 and 5.5, we provide upper bounds for the summands on the right hand side of (5.17), which we denote by $Q_k(\pi)$. In Proposition 5.4, we do this for the trivial partition consisting of a single set, for which we write $\pi_1$. In Proposition 5.5, we do this for each of the other partitions. The sum over $\Pi - \{\pi_1\}$ of the bounds for $Q_k(\pi)$ that are obtained in Proposition 5.5 will be negligible in comparison with the bound obtained for $Q_k(\pi_1)$ in Proposition 5.4. This last bound will therefore dominate the upper bound for $P_k$ that will be obtained by inserting these bounds into (5.17) of the preceding proposition.

Both Propositions 5.4 and 5.5 employ the elementary upper bounds for $J_{k,h}(s)$,

\begin{equation}
J_{k,h}(s) \leq \left(4(\frac{qs}{h})^h/h! \right) \wedge 1 \quad \text{for } s \leq h/4q_k, \\
\leq 1 \quad \text{for } s > h/4q_k,
\end{equation}

which one obtains by dominating the series in (5.16) by the geometric series $((\frac{qs}{h})^h/h!) \sum_{i=0}^{\infty} (\frac{3}{4})^i$, for $s \leq h/4q_k$.

**Proposition 5.4.** Suppose that

\begin{equation}
Q_k(\pi_1) = \int_0^\infty (k+s)J_{k,h_T}(s) F(ds),
\end{equation}

where $F(\cdot)$ satisfies (5.4) and $J_{k,h_T}(s)$ is chosen as above, with $h_T \geq 6$, and suppose that $k \geq k_0$, with (5.14) and 5.15 both holding. Then,

\begin{equation}
Q_k(\pi_1) \leq 55Dc_2(\frac{q_k}{h_T})^{1/(D-1)}.
\end{equation}

**Proof.** Throughout the proof, we will abbreviate by setting $h_T = h$. We begin the argument by decomposing the integral into the three parts, $\int_0^k$, $\int_k^{h/27q_k}$ and $\int_{h/27q_k}^\infty$, which we analyze separately.

Since $k+s \leq 2k$ for $s \in [0,k]$, it is easy to check that

\begin{equation}
\int_0^k (k+s)J_{k,h}(s) F(ds) \leq 8k^{h+1}q_k^h/h!.
\end{equation}

One has $k \geq s_0$ for $s_0$ in (5.4). Applying (5.4) and $k+s \leq 2s$, and substituting $t = q_k s/h$, one sees that the second integral is bounded above by

\begin{equation}
(8D/(D-1))c_2 \int_0^{1/27} q_k^{1/(D-1)}(t^{2/3}h)^h/h!t^{(\frac{2}{3}-\frac{D}{D-1})} dt.
\end{equation}
Since $h \geq 6$, one can check that $(t^{2/3}h/h!) \leq 3^{-h}$ and $t^{(h-D)} \leq 1$ for $t \leq 1/27$. Therefore, \((5.22)\) is bounded above by

\[
(5.23) \quad \frac{8}{27}(D/(D-1))c_2 3^{-h} q_k^{1/(D-1)} \leq c_2 3^{-h} q_k^{1/(D-1)}.
\]

Applying \((5.4)\), the third integral is at most

\[
(5.24) \quad 2(D/(D-1))c_2 \int_0^{h/27} s^{-D/(D-1)} ds \leq 54Dc_2(q_k/h)^{1/(D-1)}.
\]

On account of \((5.15)\) and $q_k \leq c_2$, the bound for the third integral is clearly the dominant term. Combining the bounds for the three integrals therefore implies that

\[
Q_k(\pi_1) \leq 55Dc_2(q_k/h)^{1/(D-1)},
\]

which is the bound in \((5.20)\). \hfill \(\square\)

**Proposition 5.5.** Suppose that

\[
Q_k(\pi) = (3k)^{m_\pi - 1} \prod_{\ell=1}^{m_\pi - 1} \left( \int_0^\infty J_{k,h_{t_\ell}}(s) F(ds) \right) \times \int_0^{\infty} (k + s) J_{k,h_{m_\pi}}(s) F(ds),
\]

where $F(\cdot)$ satisfies \((5.4)\) and $J_{k,h_{t_\ell}}(s)$ is chosen as above, with $h_T \geq 5$, and suppose that $k \geq k_0$, with \((5.14)\) and \((5.15)\) both holding. Then,

\[
Q_k(\pi) \leq 81D^2(c_2 + 1)^2 a_{h_T} 2^{h_T} h_T^{h_T} (3k)^{h_T} q_k^{D/(D-1)}
\]

for each $\pi \in \Pi_k - \{\pi_1\}$.

In order to demonstrate Proposition 5.5, we will categorize each partition in $\Pi_k - \{\pi_1\}$ as one of three types, based on the sizes and indices of its constituent sets $G_\ell$, \(\ell = 1, \ldots, m_\pi\). We will say $G_\ell$ is *large* if $h_\ell \geq 3$ and *small* if $h_\ell \leq 2$; we will also distinguish between sets $G_\ell$ with $\ell < m_\pi$ and $\ell = m_\pi$. We will say that a partition $\pi$ is of type (I) if at least one of its sets $G_\ell$, with $\ell < m_\pi$, is large; that it is of type (II) if $G_{m_\pi}$ is large, but all of the other sets are small; and that it is of type (III) if none of its sets is large, but at least two sets $G_{\ell_1}$ and $G_{\ell_2}$, with $\ell_1 < \ell_2 < m_\pi$ are small. It is easy to check that, for any $h_T \geq 5$, the three types of sets partition $\Pi_k - \{\pi_1\}$. 
Proof of Proposition 5.5. We will show separately that (5.26) holds when $\pi$ is a member of any of the above three types of partitions. We will first bound the above integrals for the large and small sets $G_{\ell}$, for both $\ell = m_{\pi}$ and $\ell < m_{\pi}$, and will then apply these bounds to the three types of partitions. When convenient, we abbreviate by setting $h_{\ell} = h$.

Applying almost the same reasoning as in the proof of Proposition 5.4, one obtains, for large $G_{m_{\pi}}$,

$$\int_0^{\infty} (k + s) J_{k,h_{m_{\pi}}} (s) F(ds) \leq 2Dc_2 h_{m_{\pi}}^q q_k^{1/(D-1)}. \quad (5.27)$$

One decomposes the integral into the parts $\int_0^{k}, \int_k^{h/q_k}$ and $\int_{h/q_k}^{\infty}$. A bound for the first integral is again given by the right hand side of (5.21) and a bound for the third integral is given by $2Dc_2(q_k/h)^{1/(D-1)}$. For the second integral, one obtains the bound $c_2 h^{h/q} q_k^{1/(D-1)}$, after substituting $t = q_k s/h$ as before. Instead of (5.22), one employs

$$8(D/(D-1)) c_2 \int_0^1 q_k^{1/(D-1)} \frac{h^h}{h!} t^{(h-D-1)} dt \quad (5.28)$$

as an intermediate bound for the second integral, to which one applies $t^{(h-D-1)} \leq 1$; the acquired factor $h^h$ will not cause difficulties in the present context. For $k \geq k_0$, the bound in (5.27) follows from the bounds on the three integrals, on account of (5.15) and $q_k \leq c_2$.

Similar reasoning can be applied for large $G_{\ell}$, with $\ell < m_{\pi}$, to obtain the upper bound

$$\int_0^{\infty} J_{k,h_{\ell}} (s) F(ds) \leq 2c_2 h_{\ell}^q q_k^{D/(D-1)}. \quad (5.29)$$

One decomposes the integral into the parts $\int_0^{s_0}, \int_{s_0}^{h/q_k}$ and $\int_{h/q_k}^{\infty}$. The first integral is at most $s_0 h_{\ell} \leq s_0 h_{\ell}^3$ and the second integral is at most $c_2 q_k^{D/(D-1)}$. For the second integral, one obtains the upper bound $c_2 h_{\ell}^q q_k^{D/(D-1)}$, after substituting $t = q_k s/h$. Instead of (5.22) or (5.28), one employs

$$4(D/(D-1)) c_2 \int_0^1 q_k^{D/(D-1)} \frac{h^{-1}}{h!} t^{(h-D-1)} dt, \quad (5.30)$$

as an intermediate bound for the second integral, to which one applies $t^{(h-D-1)} \leq 1$. Since $1/q_k \geq s_0^h$, the bound in (5.27) follows from the bounds on the three integrals.
For small $G_{\ell}$ with $\ell < m_\pi$, one obtains the upper bound
\begin{equation}
(5.31) \quad \int_0^\infty J_{k,h}(s) F(ds) \leq 9D(c_2 + 1)s_h q_k.
\end{equation}

As in the previous case, one decomposes the integral into the parts $\int_0^{s_0}$, $\int_{s_0}^{h/q_k}$ and $\int_{h/q_k}^{\infty}$. The same estimates show that the first integral is at most $s_0 h q_k \leq s_0 h q_k$ and the third integral is at most $c_2 q_k^{D/(D-1)}$. For the second integral, one obtains the upper bounds
\begin{equation}
(5.32) \quad \frac{4(D/(D-1))c_2}{h} \int_{s_0}^{h/q_k} q_k \frac{h^{h-1}}{h!} s^{-D/(D-1)} ds \leq 8Dc_2 s_0 q_k,
\end{equation}

with the inequality using $h \leq 2$. The bound in (5.31) follows from the bounds on the three integrals.

For small $G_{m_\pi}$, the upper bound
\begin{equation}
(5.33) \quad \int_0^\infty (k + s) J_{k,m_\pi}(s) F(ds) \leq k + 1 \leq 2k
\end{equation}
follows from $J_{k,m_\pi}(s) \leq 1$, since $F(\cdot)$ has mean 1.

We also note that, for $G_{\ell}$ with $\ell < m_\pi$,
\begin{equation}
(5.34) \quad \int_0^\infty J_{k,h}(s) F(ds) \leq 1
\end{equation}
trivially holds.

We now combine the upper bounds in (5.27), (5.29), (5.31) (5.33) and (5.34) to obtain upper bounds for the right hand side of (5.25), for large $k$. When $\pi$ is a type (I) partition, it follows from (5.29), (5.33) and (5.34) that
\begin{equation}
(5.35) \quad Q_k(\pi) \leq 2c_2 h_T h_T (3k)^m q_k^{D/(D-1)};
\end{equation}

when $\pi$ is a type (II) partition, it follows from (5.27), (5.31) and (5.34) that
\begin{equation}
(5.36) \quad Q_k(\pi) \leq 18D^2(c_2 + 1)^2 s_0 h_T h_T (3k)^m q_k^{D/(D-1)};
\end{equation}

and when $\pi$ is a type (III) partition, it follows from (5.31), (5.33) and (5.34) that
\begin{equation}
(5.37) \quad Q_k(\pi) \leq 81D^2(c_2 + 1)^2 s_0^2 h_T (3k)^m q_k^2.
\end{equation}

The right hand side of (5.26) is greater than each of the quantities in (5.35)–(5.37). Consequently, (5.26) holds for all $\pi \in \Pi_k - \{\pi_1\}$, as desired. \(\square\)
Employing Propositions 5.3, 5.4 and 5.5, and the induction hypothesis (5.11), we now complete the proof of Proposition 5.2.

**Proof of Proposition 5.2.** We will demonstrate that the inequality in (5.11) holds for \( i = k \), provided it holds for \( i = k_0, \ldots, k - 1 \), for \( h_T \) and \( a_2 \) satisfying (5.12) and (5.13), and for \( k_0 \) satisfying the inequalities in (5.14) and on each side. By induction, it will follow that

\[
P_k \leq C_{13}e^{-a_2 k} \quad \text{for all } k \geq k_0.
\]

By Proposition 5.3,

\[
P_k \leq 3 \sum_{\pi \in \Pi_k} Q_k(\pi) \leq 3Q_k(\pi_1) + 3 \cdot 2^{h_T} \max_{\pi \in \Pi_k - \{\pi_1\}} Q_k(\pi).
\]

On account of (5.14) and (5.15), it follows from the bounds in (5.20) and (5.26), for \( Q_k(\pi_1) \) and for \( Q_k(\pi), \pi \in \Pi_k - \{\pi_1\} \), that the first term on the right hand side of (5.39) dominates the second term, and therefore

\[
P_k \leq 220Dc_2(q_k/h_T)^{1/(D-1)}.
\]

Substituting for \( q_k \) and then for \( M \), this is at most

\[
\left( 220D^2 c_2 h_T^{-1/(D-1)} e^{a_2 h_T} \right) C_{13} e^{-a_2 k}.
\]

Upon substitution of the value for \( h_T \) in (5.12) and \( a_2 = 1/h_T \), the quantity inside the parentheses in (5.41) is less than 1. Also, by replacing the term \( h_T^{-1/(D-1)} \) by 1, it is easy to see that the quantity inside the parentheses is again less than 1, for \( a_2 = \frac{1}{h_T} \log \left( (220D^2 c_2)^{1/(D-1)} \right) \). So, in either case, the inequality in (5.11) holds for \( i = k \). This implies (5.38).

With a large enough choice of \( C_{13} \), (5.38) extends to all \( k \geq 0 \). This implies (5.5) of Proposition 5.2 with \( r_D(c_2) = a_2 \), for this choice of \( C_{13} \). Moreover, as \( c_2 \downarrow 0 \), one has \( a_2 \uparrow \infty \), and so (5.6) also holds. This completes the proof of Proposition 5.2. \( \square \)

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