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REPORT *RAPPORT*

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Probability, Networks and Algorithms

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REPORT PNA-R0812 SEPTEMBER 2008

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ISSN 1386-3711

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ABSTRACT
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2000 Mathematics Subject Classification: 60K25, 60K05
Keywords and Phrases: queueing, Gaussian processes, large deviations, transience

Transient characteristics of Gaussian queues

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September 22, 2008

Abstract

This paper analyzes transient characteristics of Gaussian queues. More specifically, we determine the logarithmic asymptotics of $\mathbb{P}(Q_0 > pB, Q_{TB} > qB)$, where Q_t denotes the workload at time t. For any pair (p, q) three regimes can be distinguished: (A) For small values of T, one of the events $\{Q_0 > pB\}$ and $\{Q_{TB} > qB\}$ will essentially imply the other. (B) Then there is an intermediate range of values of T for which it is to be expected that both $\{Q_0 > pB\}$ and $\{Q_{TB} > qB\}$ are tight (in that none of them essentially implies the other), but that the time epochs 0 and T lie in the same busy period with overwhelming probability. (C) Finally, for large T still both events are tight, but now they occur in different busy periods with overwhelming probability. For the short-range dependent case explicit calculations are presented, whereas for the long-range dependent case structural results are proven.

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1 Introduction

Over the past decade a substantial research effort has been devoted to the analysis of queues with Gaussian input [12, 14, 18]. It is noted, however, that the vast majority of papers on these *Gaussian queues* address issues related to the corresponding *steady-state* distribution. These results are predominantly of an asymptotic nature, in that they identify the tail asymptotics [8, 10, 15, 17]. Importantly, however, so far hardly any attention has been paid to *transient* properties. A notable exception is the recent paper [9] where asymptotics of transient probabilities under a so-called many-sources scaling were found (for specific Gaussian inputs) .

In more detail, in [9] the following model was considered. A queue is fed by n i.i.d. Gaussian processes with stationary increments, and emptied at a constant rate nc (with c large enough to ensure stability). With Q_t^n denoting the buffer content at time t, the logarithmic asymptotics

$$\lim_{n\to\infty} \frac{1}{n} \log \mathbb{P}(Q_0^n > np, Q_T^n > nq)$$

were determined for T large (assuming the queue is in stationarity at time 0). A crucial element in the reasoning is that for T large enough, the time epochs 0 and T lie in separate busy periods, thus simplifying the analysis substantially. A conclusion drawn in [9] is that the correlation structure of the input process essentially carries over to the workload process.

In the present paper we consider a different scaling, viz. the so-called *large-buffer scaling*. Then the queue is fed by just a single Gaussian process with stationary increments (with the associated variance curve denoted by $v(\cdot)$), and emptied at a constant rate C. With Q_t denoting the buffer content at time t, the first goal of this paper is to determine the decay rate

$$\lim_{B\to\infty} \frac{v(B)}{B^2} \log \mathbb{P}(Q_0 > pB, Q_{TB} > qB). \tag{1}$$

Interestingly, in view of earlier work, see e.g. [13] and [20, Section 11.7], multiple regimes are envisaged. For small values of T, typically one of the events $\{Q_0 > pB\}$ and $\{Q_{TB} > qB\}$ will essentially imply the other; in the sequel we call this regime (A). For instance if p is substantially larger than q (and T small), then it is likely that (1) equals the decay rate of just $\mathbb{P}(Q_0 > pB)$ — we say that in this case the event $\{Q_0 > pB\}$ is 'tight'. Likewise, if q is substantially larger than p, then we expect that only $\{Q_{TB} > qB\}$ is tight. Then there is an intermediate range of values of T, regime (B), for which it is to be expected that both $\{Q_0 > pB\}$ and $\{Q_{TB} > qB\}$ are tight, but that the time epochs 0 and T lie in the same busy period with overwhelming probability. Finally, for large T still both events are tight, but now they occur in different busy periods with overwhelming probability; to this regime we refer as Regime (C). A second goal of the paper is to make the above statements rigorous.

This paper is organized as follows. In Section 2 we present the model and give a problem description. Then Section 3 introduces additional notation, and we establish a useful reduction property. Our first main result, namely an explicit representation of the decay rate (1), is given in Section 4. The cases of short-range dependent and long-range dependent input are dealt with in Section 5; in both cases the regimes (A), (B), and (C) are studied.

2 Model and problem description

Let $\{X(t) : t \in \mathbb{R}\}$ be a Gaussian process with *stationary increments*, starting off at 0 (that is, $X(0) = 0$, a.s.). Without loss of generality we assume that the process be *centered*, i.e., $\mathbb{E}X(t) = 0$ for any t. Furthermore, the variance function is given through $v(t) := \mathbb{V}\mathrm{ar}(X(t))$.
Throughout the paper we impose the following assumption.

Assumption 2.1. *$v(\cdot)$ is a regularly varying function (at ∞) of index $\alpha \in (0, 2)$.*

In this paper we analyze a queue fed by input process $X(\cdot)$, emptied at a constant rate $C > 0$. More formally, we define the steady-state buffer content process $\{Q_t : t \geq 0\}$ by the following representation:

$$Q_t = \sup_{s\geq 0}(A(t-s,t) - Cs), \tag{2}$$

where $A(s, t) := X(t) - X(s)$ for $s \leq t$, to be interpreted as the amount of traffic having entered the system between s and t.

As mentioned in the introduction, this paper focuses on analyzing transient properties of the buffer content process, or more specifically, we wish to determine, under Assumption 2.1, the asymptotics of

$$\begin{aligned} N(B) \equiv N_{p,q,T}(B) &:= \mathbb{P}\left(Q_0 > pB, Q_{TB} > qB\right) \\ &= \mathbb{P}(\exists s \geq 0 : A(-s, 0) > pB + Cs, \exists t \geq 0 : A(TB - t, TB) > qB + ct); \end{aligned}$$

for B large and $p, q, T > 0$ given (the latter identity follows from a direct interpretation of the definition of the supremum in (2)).
For the univariate case these logarithmic asymptotics are known (and in fact even the *exact* asymptotics are known); these are (roughly) Weibullian:

$$\lim_{B\to\infty} \frac{v(B)}{B^2} \log \mathbb{P}(Q_0 > B) = -\frac{1}{2}\left(\frac{2}{2-\alpha}\right)^{2-\alpha}\left(\frac{2C}{\alpha}\right)^{\alpha}; \tag{3}$$

see, e.g., [4]. In Section 4 it will turn out that the nature of the decay rate (1) crucially depends on the values of p, q, and T. Typically, we will have that for p and q given and T small the joint asymptotics (1) reduce to the one-dimensional asymptotics; in light of (3) this means that for $p > q$ and T small, we have

$$\lim_{B\to\infty} \frac{v(B)}{B^2} \log \mathbb{P}\left(Q_0 > pB, Q_{TB} > qB\right) = -\frac{1}{2}\left(\frac{2p}{2-\alpha}\right)^{2-\alpha}\left(\frac{2C}{\alpha}\right)^{\alpha},$$

while for $q > p$, we have the same result but with p replaced by q. We will, for any pair (p, q), show in Section 5 that the joint asymptotics reduce to one-dimensional asymptotics if and only if T is smaller than some threshold (being the unique solution of an explicit equation). For T larger than this threshold, we may have two types of behavior: the queue can have been empty (with overwhelming probability) or not. Typically, when T is large it is more likely that the buffer content first reaches pB at time 0, then drops to 0, and only just before TB increases again, to reach level qB at time TB; for smaller T (with overwhelming probability) the queue has not been empty between 0 and TB. In Section 5 we will explicitly give a threshold above which time 0 and time TB lie in separate busy periods (with overwhelming probability).

3 Notation and preliminaries

In this section we first derive a useful reduction property. We then introduce the notation that we use throughout the paper.

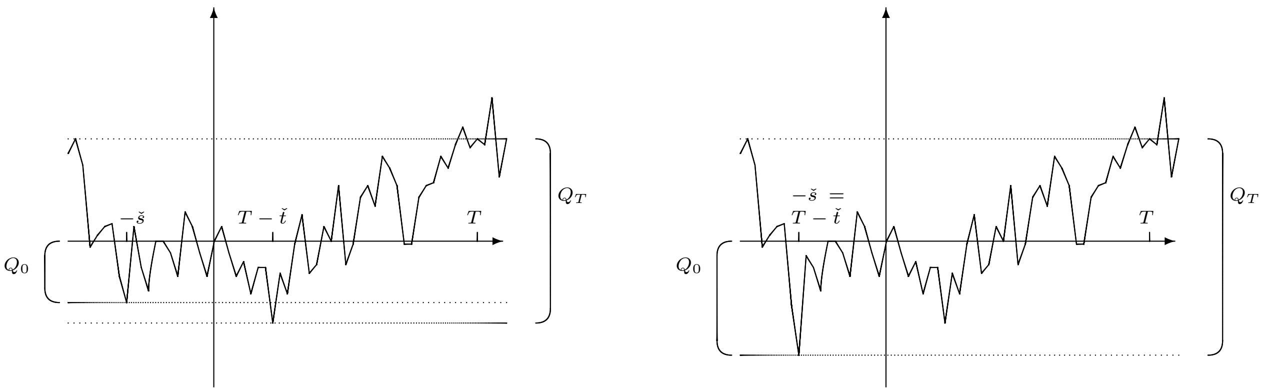

Figure 1: Proof of Lemma 3.1. In the left picture the busy period in which T is contained starts after time 0; in the right picture the busy periods in which 0 and T are contained start at the same moment. Here $Q_u := \sup_{v\leq u} A(v,u) - C(u-v)$.

3.1 Reduction property

The following result appears to be useful later on. After the proof, we also give a more intuitive reasoning why it is valid. Let

$$\mathscr{E}_T := \{(s,t) : s \geq 0, t \in [0,T) \cup \{T+s\}\}.$$

Lemma 3.1. *For any* $p,q,T>0$,

$$\begin{aligned}&\mathbb{P}\left(\exists s\geq 0, t\geq 0 : A(-s,0) - Cs > p, A(T-t,T) - Ct > q\right)\\ &\quad= \mathbb{P}\left(\exists (s,t)\in\mathscr{E}_T : A(-s,0) - Cs > p, A(T-t,T)-Ct>q\right).\end{aligned}$$

Proof. Let $\check{s}$ be the optimizer in $\sup_{s\geq 0} A(-s,0) - Cs$. Also,

$$\begin{aligned}\mathscr{A}_T &:= \{\exists (s,t)\in\mathscr{E}_T : A(-s,0)-Cs>p, A(T-t,T)-Ct>q\},\\ \mathscr{A} &:= \{\exists (s,t)\in\mathbb{R}_+^2 : A(-s,0)-Cs>p, A(T-t,T)-Ct>q\}.\end{aligned}$$

We prove the stated by showing $\mathscr{A}_T = \mathscr{A}$. As $\mathscr{A}_T \subseteq \mathscr{A}$, it is left to show $\mathscr{A}_T \supseteq \mathscr{A}$.
Take a realization from $\mathscr{A}$ and suppose for $t \in [T, T+\check{s}) \cup (T+\check{s},\infty)$ we have that $A(T-t,T)-Ct>q$ (as for all other t the claimed is clear). Then also, by definition of $\check{s}$,

$$\begin{aligned}&A(-\check{s},T) - C(T+\check{s}) = (A(-\check{s},0) - C\check{s}) + (A(0,T) - CT)\\ &\quad\geq (A(T-t,0) - C(t-T)) + (A(0,T)-CT) = A(T-t,T) - Ct > q.\end{aligned}$$

Hence the realization was also in $\mathscr{A}_T$, which proves the stated. □

Remark 3.2. An alternative, more intuitive but essentially equivalent, line of reasoning is the following. Let $\check{t}$ be the optimizer in $\sup_{t\geq 0} A(T-t,T) - Ct$. The optimizers $\check{s}$ and $\check{t}$ can be interpreted as the starting epochs of the busy periods in which 0 and T, respectively, are contained.

- It is clear that $\check{t}$ cannot lie in $(T, T+\check{s})$: it cannot be that a busy period starts in $(-\check{s}, 0)$, as the buffer has been non-empty in this interval all the time (since the busy period in which 0 is contained started at $\check{s}$).

- Similarly, $\check{t}$ cannot lie in $(T+\check{s},\infty)$: it cannot be that a busy period starts before $\check{s}$ and lasts till at least T, as the buffer was empty just before $\check{s}$ (since a busy period started at $\check{s}$).

The following corollary is an immediate consequence of Lemma 3.1. It means that we can restrict ourselves to $(s,t)\in\mathscr{D}_B$ rather than $\mathbb{R}^2$ when analyzing $N(B)$.

Corollary 3.3. *With $\mathscr{D}_B := \mathscr{E}_{TB}$,*

$$N(B)=\mathbb{P}\left(\exists(s,t)\in\mathscr{D}_B : A(-s,0)-Cs>pB, A(TB-t,TB)-Ct>qB\right).$$

3.2 Notation

In the sequel we extensively use the following Gaussian processes:

$$Y_B(s):=\frac{A(-s,0)}{pB+Cs};\;\; Z_B(t)\equiv Z_{B,T}(t):=\frac{A(TB-t,TB)}{qB+Ct};$$

observe that neither $Y_B(\cdot)$ nor $Z_B(\cdot)$ has stationary increments. Define the 'standard deviation curve' by $\sigma(s):=\sqrt{v(s)}$. Also

$$\sigma_Y(s):=\sqrt{\mathbb{V}\mathrm{ar}Y_B(s)}=\frac{\sigma(s)}{pB+Cs};\;\;\sigma_Z(t):=\sqrt{\mathbb{V}\mathrm{ar}Z_B(t)}=\frac{\sigma(t)}{qB+Ct}.$$

Notice that $\sigma_Y(s),\sigma_Z(t)$ depend on p,q and B, but not on T. Furthermore, we define

$$\gamma(s,t)\equiv\gamma_{B,p,q}(s,t)=\min\left\{\frac{\sigma_Y(s)}{\sigma_Z(t)},\frac{\sigma_Z(t)}{\sigma_Y(s)}\right\}.$$

We also define the correlation between $Y_B(s)$ and $Z_B(t)$, which does not depend on p and q:

$$r(s,t)\equiv r_{B,T}(s,t)=\mathbb{C}\mathrm{orr}(Y_B(s),Z_B(t))=\frac{\mathbb{C}\mathrm{ov}(A(-s,0),A(TB-t,TB))}{\sigma(s)\sigma(t)}.$$

A crucial role will be played by the function

$$\xi_{X;B}(s,t)\equiv\xi_{X;B,p,q,T}(s,t):=\frac{1}{2\min\{\sigma_Y^2(s),\sigma_Z^2(t)\}}\left(1+\frac{(\gamma(s,t)-r(s,t))^2}{1-r^2(s,t)}I(s,t)\right),$$

with $I(s,t):=1_{\{r(s,t)<\gamma(s,t)\}}$. As will appear later on, it turned out practical to add the subscript 'X' that indicates the underlying Gaussian process (that in turn defines the processes Y_B and Z_B).

4 General results

The following general result can be deduced. It is a generalization of the one-dimensional logarithmic asymptotics of [4], and extension of [19], where the two-dimensional logarithmic asymptotics for the class of centered Gaussian processes was considered. The only assumption required is that the variance curve is regularly varying at ∞. Let $\mathbb{B}_\alpha(\cdot)$ denote fBm with Hurst parameter $H=\alpha/2$.

Theorem 4.1. *Assume that $\{X(t):t\in\mathbb{R}\}$ satisfies Assumption 2.1 with $\alpha\in(0,2)$. Then for each $p,q,T>0$*

$$\lim_{B\to\infty}\frac{v(B)}{B^2}\log N(B)=-\inf_{s\geq 0}\inf_{t\in[0,T)\cup\{T+s\}}\xi_{\mathbb{B}_\alpha;1}(s,t).$$

Notice that the above theorem entails that, under Assumption 2.1, the bivariate asymptotics of $N(B)$ reduce to the bivariate asymptotics of a queue with fBm input. In the remainder of this section we present the complete proof of Theorem 4.1. We start by establishing a lemma that is also of independent interest.

Lemma 4.2. *For arbitrary* $0 < \underline{\varepsilon} < \overline{\varepsilon} < \infty$,

(i) *Uniformly in* $s \in [\underline{\varepsilon}, \overline{\varepsilon}]$, *as* $B \to \infty$,

$$\sigma_Y^2(sB)\frac{B^2}{v(B)} \to \frac{s^\alpha}{(Cs+p)^2};$$

(ii) *Uniformly in* $t \in [\underline{\varepsilon}, \overline{\varepsilon}]$, *as* $B \to \infty$,

$$\sigma_Z^2(tB)\frac{B^2}{v(B)} \to \frac{t^\alpha}{(Ct+q)^2};$$

(iii) *Uniformly in* $(s,t) \in [\underline{\varepsilon}, \overline{\varepsilon}]^2$, *as* $B \to \infty$,

$$\gamma(sB,tB) \to \min\left\{\frac{s^{\alpha/2}/(p+Cs)}{t^{\alpha/2}/(q+Ct)}, \frac{t^{\alpha/2}/(q+Ct)}{s^{\alpha/2}/(p+Cs)}\right\};$$

(iv) *Uniformly in* $(s,t) \in [\underline{\varepsilon}, \overline{\varepsilon}]^2$, *as* $B \to \infty$,

$$r(sB,tB) \to \frac{(T+s)^\alpha - T^\alpha + |T-t|^\alpha - |T-t+s|^\alpha}{2s^{\alpha/2}t^{\alpha/2}}$$

Proof. The proof of Lemma 4.2 follows straightforwardly from Assumption 2.1, combined with standard properties of regularly varying functions. □

Lemma 4.3. *For each* $0 < \underline{\varepsilon} < \overline{\varepsilon} < \infty$,

$$\xi_{X;B}(sB,tB)\cdot\frac{v(B)}{B^2} \to \xi_{\mathbb{B}_\alpha;1}(s,t)$$

as $B \to \infty$ *uniformly in* $(s,t) \in [\underline{\varepsilon}, \overline{\varepsilon}]^2$.

Proof. The claim follows from applying Lemma 4.2 to the definition of $\xi_{X;B}(s,t)$. □

Lemma 4.4. *For each* $0 < \underline{\varepsilon} < \overline{\varepsilon} < \infty$,

$$\lim_{B\to\infty}\frac{v(B)}{B^2}\log\mathbb{P}\left(\begin{array}{l} A(-sB,0) - CsB > pB; \\ A(TB-tB,TB) - CtB > qB \end{array}\right) = -\xi_{\mathbb{B}_\alpha;1}(s,t)$$

uniformly in $(s,t) \in [\underline{\varepsilon}, \overline{\varepsilon}]^2$.

Proof. Follows from the combination of classical asymptotics of the bivariate Normal random variable, in conjunction with Lemma 4.3. □

Corollary 3.3 indicated that we can restrict ourselves, when analyzing $N(B)$, to $s \geq 0$ and $t \in [0,TB) \cup \{TB+s\}$. The following lemma is useful in that we can restrict ourselves, for B large, even further, viz. to finite s and t that are bounded away from zero. This property will appear to be useful later on when applying the standard inequalities for suprema of Gaussian processes.

Lemma 4.5. *There exist* $\bar{\varepsilon} > \underline{\varepsilon} > 0$ *such that*

$$N(B) = \mathbb{P}\left(\begin{array}{c} \exists s \in [\underline{\varepsilon}B, \bar{\varepsilon}B] : \exists t \in [\underline{\varepsilon}B, TB) \cup \{TB + s\} : \\ A(-s,0) - Cs > Bp, A(TB-t,TB) - Ct > Bq \end{array}\right)(1+o(1)),$$

as $B \to \infty$.

Proof. In view of Corollary 3.3 it suffices to establish an upper bound. To this end, first define, for given $0 < \underline{\varepsilon} < \bar{\varepsilon}$ (where $\underline{\varepsilon} < T$),

$$\mathscr{C}_B := \{(s,t) : s \in [\underline{\varepsilon}B, \bar{\varepsilon}B], t \in [\underline{\varepsilon}B, TB) \cup \{TB + s\}\}.$$

An obvious inequality is

$$\mathbb{P}\left(\exists (s,t) \in \mathscr{D}_B : A(-s,0) - Cs > Bp, A(TB-t,TB) - Ct > Bq\right) \le \pi_1 + \pi_2,$$

where $\pi_1 \equiv \pi_1(B)$ and $\pi_2 \equiv \pi_2(B)$ are given through

$$\pi_1 := \mathbb{P}\left(\exists (s,t) \in \mathscr{C}_B : A(-s,0) - Cs > Bp, A(TB-t,TB) - Ct > Bq\right);$$

$$\pi_2 := \mathbb{P}\left(\exists (s,t) \in \mathscr{D}_B \setminus \mathscr{C}_B : A(-s,0) - Cs > Bp, A(TB-t,TB) - Ct > Bq\right).$$

Observe that it suffices to show that $\pi_2 = o(\pi_1)$ as $B \to \infty$. We do so by bounding π_1 from below and π_2 from above, as follows.
Let $\bar{\varepsilon} > \underline{\varepsilon} > 0$ be such that $\bar{s} := \alpha p/((2-\alpha)C) \in [\underline{\varepsilon}, \bar{\varepsilon}]$. Then, by virtue of Lemma 4.4, we have

$$\begin{aligned} \log \pi_1 &\ge \log \mathbb{P}(A(-\bar{s}B, 0) - C\bar{s} > pB; A(-\bar{s}B, TB) - C(\bar{s}+T)B > qB) \\ &= -\frac{B^2}{v(B)}\xi_{\mathbb{B}_\alpha;1}(\bar{s}, \bar{s}+T)(1+o(1)), \end{aligned} \tag{4}$$

as $B \to \infty$. Moreover, for each $B > 0$, it holds that $\pi_2 \le \pi_3 + \pi_4$, with

$$\begin{aligned} \pi_3 \equiv \pi_3(B) &:= \mathbb{P}\left(\sup_{s \in [0, \underline{\varepsilon}B]} (A(-s,0) - Cs) > pB\right); \\ \pi_4 \equiv \pi_4(B) &:= \mathbb{P}\left(\sup_{s \in [\bar{\varepsilon}B, \infty)} (A(-s,0) - Cs) > pB\right) \end{aligned}$$

By applying Borell's inequality (see, e.g., Adler [2, page 43]), we can bound both probabilities from above. Let us first focus on π_3. For B large enough,

$$\begin{aligned} \log \pi_3 &= \log \mathbb{P}\left(\sup_{s \in [0, \underline{\varepsilon}B]} \frac{A(-s,0)}{Cs + pB} > 1\right) \\ &\le -\frac{1}{2}\inf_{s \in [0, \underline{\varepsilon}B]} \frac{(Cs+pB)^2}{v(s)} \le -\frac{1}{2}\frac{p^2B^2}{v(\underline{\varepsilon}B)} \le -\frac{p^2}{4\underline{\varepsilon}^\alpha}\frac{B^2}{v(B)}. \end{aligned}$$

Analogously, for any $\zeta \le (2-\alpha)/2$ and B sufficiently large,

$$\begin{aligned} \log \pi_4 &\le -\frac{1}{2}\inf_{s \in [\bar{\varepsilon}B, \infty)} \frac{(Cs+pB)^2}{v(s)} \\ &= -\frac{1}{2}\inf_{s \in [\bar{\varepsilon}, \infty)} (Cs+p)^2 \frac{v(B)}{v(sB)}\frac{B^2}{v(B)} \le -\frac{1}{2}\inf_{s \in [\bar{\varepsilon}, \infty)} (1-\zeta)\frac{(Cs+p)^2}{s^{\alpha+\zeta}}\frac{B^2}{v(B)}. \end{aligned}$$

We have now collected all the prerequisites to prove the claim $\pi_2 = o(\pi_1)$ as $B \to \infty$. First realize that $p^2/(4\underline{\varepsilon}^\alpha) \to \infty$, as $\underline{\varepsilon} \to 0$, and (because $s^{2-\alpha-\zeta} \to \infty$ as $s \to \infty$)

$$\inf_{s\in[\overline{\varepsilon},\infty)} \frac{(Cs+p)^2}{s^{\alpha+\zeta}} \to \infty$$

as $\overline{\varepsilon} \to \infty$. This means that, in order to have $\pi_2 = o(\pi_1)$, we can choose $\overline{\varepsilon} > \underline{\varepsilon} > 0$ such that

$$\xi_{\mathbb{B}_\alpha;1}(\bar{s}, \bar{s}+T) < \frac{p^2}{4\underline{\varepsilon}^\alpha} \quad \text{and} \quad \xi_{\mathbb{B}_\alpha;1}(\bar{s}, \bar{s}+T) < \frac{1}{2} \inf_{s\in[\overline{\varepsilon},\infty)} (1-\zeta) \frac{(Cs+p)^2}{s^{\alpha+\zeta}}.$$

This completes the proof. □

Proof of Theorem 4.1. In this proof (and in the sequel), we choose $\underline{\varepsilon}$ and $\overline{\varepsilon}$ as indicated in Lemma 4.5. We subsequently prove the lower bound and upper bound.

Lower bound. We use the argumentation of [18]. An evident lower bound is

$$\begin{aligned} N(B) &\geq \mathbb{P}\left(\exists (s,t) \in \mathcal{C}_B : A(-s,0) - Cs > Bp, A(TB-t, TB) - Ct > Bq\right) \\ &\geq \sup_{(s,t)\in\mathcal{C}_B} \mathbb{P}\left(A(-s,0) - Cs > Bp, A(TB-t, TB) - Ct > Bq\right). \end{aligned}$$

Hence, due to Lemma 4.4, we have

$$\log N(B) \cdot \frac{v(B)}{B^2} \quad \geq \quad - \inf_{s\in[\underline{\varepsilon},\overline{\varepsilon}];t\in[\underline{\varepsilon},T)\cup\{T+s\}} \xi_{\mathbb{B}_\alpha;1}(s,t).$$

Now it suffices to observe that, for appropriately chosen $\underline{\varepsilon}, \overline{\varepsilon}$,

$$\inf_{s\in[\underline{\varepsilon},\overline{\varepsilon}];t\in[\underline{\varepsilon},T)\cup\{T+s\}} \xi_{\mathbb{B}_\alpha;1}(s,t) = \inf_{s\in[0,\infty);t\in[0,T)\cup\{T+s\}} \xi_{\mathbb{B}_\alpha;1}(s,t),$$

which follows from the fact that $\sigma_Y(s) \to 0$ as $s \to 0$ or $s \to \infty$, and $\sigma_Z(t) \to 0$ as $t \to 0$.

Upper bound. The upper bound is considerably more involved than the lower bound. Due to Lemma 4.5 we have

$$\begin{aligned} N(B) &\leq \mathbb{P}\left(\exists (s,t) \in \mathscr{C}_B : A(-s,0) - Cs > Bp, A(TB-t, TB) - Ct > Bq\right) (1+o(1)) \\ &= \mathbb{P}\left(\exists (s,t) \in \mathscr{C}_B : Y_B(s) > 1, Z_B(t) > 1\right) (1+o(1)). \end{aligned}$$

In this proof we need the following notions:

$$\alpha(s,t) \equiv \alpha_{Y,Z}(s,t) := 1 - r(s,t) \cdot \max\{r(s,t), \gamma(s,t)\}$$

$$\beta(s,t) \equiv \beta_{Y,Z}(s,t) := \max\{r(s,t), \gamma(s,t)\} - r(s,t)$$

and

$$\mathscr{D}_B^{(1)} := \{(s,t) \in \mathscr{D}_B : \sigma_Y(s) \leq \sigma_Z(t)\}; \ \ \mathscr{D}_B^{(2)} := \{(s,t) \in \mathscr{D}_B : \sigma_Y(s) > \sigma_Z(t)\}.$$

The union bound trivially gives $\mathbb{P}\left(\exists (s,t) \in \mathscr{D}_B : Y_B(s) > 1, Z_B(t) > 1\right) \leq \bar{\pi}_1 + \bar{\pi}_2$, where

$$\begin{aligned} \bar{\pi}_1 &:= \mathbb{P}\left(\exists (s,t) \in \mathscr{D}_B^{(1)} : Y_B(s) > 1, Z_B(t) > 1\right); \\ \bar{\pi}_2 &:= \mathbb{P}\left(\exists (s,t) \in \mathscr{D}_B^{(2)} : Y_B(s) > 1, Z_B(t) > 1\right). \end{aligned}$$

We subsequently asymptotically analyze $\bar{\pi}_1$ and $\bar{\pi}_2$. The following upper bound on $\bar{\pi}_1$ is straightforward, as $\sigma_Y(s) \leq \sigma_Z(t)$ on $\mathscr{D}_B^{(1)}$:

$$\begin{aligned}
\bar{\pi}_1 &= \mathbb{P}\left(\exists(s,t)\in\mathscr{D}_B^{(1)} : \frac{Y_B(s)}{\sigma_Y(s)} > \frac{1}{\min\{\sigma_Y(s),\sigma_Z(t)\}}, \frac{Z_B(t)}{\sigma_Z(t)} > \frac{\gamma(s,t)}{\min\{\sigma_Y(s),\sigma_Z(t)\}}\right)\\
&= \mathbb{P}\left(\exists(s,t)\in\mathscr{D}_B^{(1)} : \frac{\alpha(s,t)Y_B(s)}{\sigma_Y(s)} > \frac{\alpha(s,t)}{\min\{\sigma_Y(s),\sigma_Z(t)\}}, \frac{\beta(s,t)Z_B(t)}{\sigma_Z(t)} > \frac{\beta(s,t)\gamma(s,t)}{\min\{\sigma_Y(s),\sigma_Z(t)\}}\right)\\
&\leq \mathbb{P}\left(\exists(s,t)\in\mathscr{D}_B^{(1)} : \frac{\alpha(s,t)Y_B(s)}{\sigma_Y(s)} + \frac{\beta(s,t)Z_B(t)}{\sigma_Z(t)} > \frac{\alpha(s,t)}{\min\{\sigma_Y(s),\sigma_Z(t)\}} + \frac{\beta(s,t)\gamma(s,t)}{\min\{\sigma_Y(s),\sigma_Z(t)\}}\right)\\
&= \mathbb{P}\left(\exists(s,t)\in\mathscr{D}_B^{(1)} : \frac{\min\{\sigma_Y(s),\sigma_Z(t)\}}{\alpha(s,t)+\beta(s,t)\gamma(s,t)}\left(\frac{\alpha(s,t)Y_B(s)}{\sigma_Y(s)} + \frac{\beta(s,t)Z_B(t)}{\sigma_Z(t)}\right) > 1\right)
\end{aligned}$$

We now prove that

$$\mathbb{E}\left(\sup_{(s,t)\in\mathscr{D}_B^{(1)}} \frac{\min\{\sigma_Y(s),\sigma_Z(t)\}}{\alpha(s,t)+\beta(s,t)\gamma(s,t)}\left(\frac{\alpha(s,t)Y_B(s)}{\sigma_Y(s)} + \frac{\beta(s,t)Z_B(t)}{\sigma_Z(t)}\right)\right) \to 0 \tag{5}$$

as $B\to\infty$. This is done as follows. Trivially,

$$\mathbb{E}\left(\sup_{(s,t)\in\mathscr{D}_B^{(1)}} \frac{\min\{\sigma_Y(s),\sigma_Z(t)\}}{\alpha(s,t)+\beta(s,t)\gamma(s,t)}\left(\frac{\alpha(s,t)Y_B(s)}{\sigma_Y(s)} + \frac{\beta(s,t)Z_B(t)}{\sigma_Z(t)}\right)\right) \leq \psi_1+\psi_2$$

where

$$\begin{aligned}
\psi_1 &\equiv \psi_1(B) := \mathbb{E}\left(\sup_{(s,t)\in\mathscr{D}_B^{(1)}} \frac{\min\{\sigma_Y(s),\sigma_Z(t)\}}{\alpha(s,t)+\beta(s,t)\gamma(s,t)}\frac{\alpha(s,t)Y_B(s)}{\sigma_Y(s)}\right);\\
\psi_2 &\equiv \psi_2(B) := \mathbb{E}\left(\sup_{(s,t)\in\mathscr{D}_B^{(1)}} \frac{\min\{\sigma_Y(s),\sigma_Z(t)\}}{\alpha(s,t)+\beta(s,t)\gamma(s,t)}\frac{\beta(s,t)Z_B(t)}{\sigma_Z(t)}\right).
\end{aligned}$$

Then realize that

$$\psi_1 \leq \sup_{(s,t)\in\mathscr{D}_B^{(1)}}\left(\frac{\min\{\sigma_Y(s),\sigma_Z(t)\}}{\alpha(s,t)+\beta(s,t)\gamma(s,t)}\frac{\alpha(s,t)}{\sigma_Y(s)}\right)\mathbb{E}\left(\sup_{(s,t)\in\mathscr{D}_B^{(1)}} Y_B(s)\right),$$

where, due to Lemma 4.2,

$$\sup_{(s,t)\in\mathscr{D}_B^{(1)}}\left(\frac{\min\{\sigma_Y(s),\sigma_Z(t)\}}{\alpha(s,t)+\beta(s,t)\gamma(s,t)}\frac{\alpha(s,t)}{\sigma_Y(s)}\right)$$

is bounded from above as $B\to\infty$, and following Lemma 2.3 in [4],

$$\mathbb{E}\left(\sup_{(s,t)\in\mathscr{D}_B^{(1)}} Y_B(s)\right) \to 0,$$

as $B\to\infty$. Hence $\psi_1\to 0$ as $B\to\infty$. Analogously, $\psi_2\to 0$ as $B\to\infty$. Hence, we have proved (5). The fact that (5) applies means that Borell's inequality [2, pages 43-44] yields (B large)

$$\begin{aligned}
\log\bar{\pi}_1 &\leq -\inf_{(s,t)\in\mathscr{D}_B^{(1)}} \frac{1}{2}\left(\frac{\alpha(s,t)+\beta(s,t)\gamma(s,t)}{\min\{\sigma_Y(s),\sigma_Z(t)\}}\right)^2 \Bigg/ \mathbb{E}\left(\left(\frac{\alpha(s,t)Y_B(s)}{\sigma_Y(s)} + \frac{\beta(s,t)Z_B(t)}{\sigma_Z(t)}\right)^2\right)\\
&= -\inf_{(s,t)\in\mathscr{D}_B^{(1)}} \frac{1}{2}\frac{\alpha(s,t)+\beta(s,t)\gamma(s,t)}{(1-r^2(s,t))\left(\min\{\sigma_Y(s),\sigma_Z(t)\}\right)^2}.
\end{aligned}$$

The latter expression equals, by virtue of Lemma 4.3, as $B \to \infty$,

$$
\begin{aligned}
& - \inf_{(s,t)\in\mathscr{D}_B^{(1)}} \frac{1}{2}\frac{\alpha(s,t)+\beta(s,t)\gamma(s,t)}{(1-r^2(s,t))\left(\min\{\sigma_Y(s),\sigma_Z(t)\}\right)^2} = \\
& = \ - \inf_{(s,t)\in\mathscr{D}_1^{(1)}} \frac{1}{2}\frac{\alpha(sB,tB)+\beta(sB,tB)\gamma(sB,tB)}{(1-r^2(sB,tB))\left(\min\{\sigma_Y(s),\sigma_Z(t)\}\right)^2} = -\frac{B^2}{v(B)} \inf_{(s,t)\in\mathscr{D}_1^{(1)}} \xi_{\mathbb{B}_\alpha;1}(s,t)(1+o(1)).
\end{aligned}
$$

Analogously, we have, as $B \to \infty$,

$$
\log \bar{\pi}_2 \leq -\frac{B^2}{v(B)} \inf_{(s,t)\in\mathscr{D}_1^{(2)}} \xi_{\mathbb{B}_\alpha;1}(s,t)(1+o(1)).
$$

We conclude, as $B \to \infty$,

$$
\begin{aligned}
& \frac{v(B)}{B^2}\log\mathbb{P}\left(\exists(s,t\in\mathscr{D}_B : Y_B(s)>1, Z_B(t)>1\right) \\
& \leq \ \frac{v(B)}{B^2}\log(\bar{\pi}_1+\bar{\pi}_2) \leq \frac{v(B)}{B^2}\log(2\max\{\bar{\pi}_1,\bar{\pi}_2\}) = -\inf_{(s,t)\in\mathscr{D}_1} \xi_{\mathbb{B}_\alpha;1}(s,t)(1+o(1)).
\end{aligned}
$$

This completes the proof. □

Remark 4.6. Using a different approach, based on Schilder's theorem, we can give a different representation for the rate function $\inf_{s\geq 0}\inf_{t\in[0,T)\cup\{T+s\}} \xi_{\mathbb{B}_\alpha;1}(s,t)$ in Theorem 4.1.
Assume that $X(t) = \mathbb{B}_\alpha(t)$ is a fractional Brownian motion with Hurst parameter $\alpha/2$. It appears that self-similar structure of fBm enables, for this special case, a rather straightforward proof of Thm. 4.1. First observe that

$$
\begin{aligned}
N(B) &= \mathbb{P}(\exists s\geq 0 : A(-sB,0) > pB + CsB, \exists t \geq 0 : A(TB-tB,TB) > qB + ctB) \\
&= \mathbb{P}\left(\exists s\geq 0 : \frac{A(-sB,0)}{B} > p + Cs, \exists t\geq 0 : \frac{A(TB-tB,TB)}{B} > q + Ct\right) \\
&\overset{\text{(i)}}{=} \mathbb{P}\left(\exists s\geq 0 : \frac{A(-s,0)}{B^{1-\alpha/2}} > p + Cs, \exists t\geq 0 : \frac{A(T-t,T)}{B^{1-\alpha/2}} > q + Ct\right) \\
&= \mathbb{P}\left(\exists s\geq 0 : \frac{A(-s,0)}{p+Cs} > B^{1-\alpha/2}, \exists t\geq 0 : \frac{A(T-t,T)}{q+Ct} > B^{1-\alpha/2}\right),
\end{aligned}
$$

where in equality (i) the self-similarity has been used. We are now in a position to apply the Schilder-type sample-path large deviations [3, 12]. To this end, define the set of paths causing overflow over level p at time 0, and over level q at time T, as follows:

$$
\mathscr{S}^0 := \bigcup_{s\geq 0}\mathscr{S}_s^0; \ \ \mathscr{S}^T := \bigcup_{t\geq 0}\mathscr{S}_t^T,
$$

where $\mathscr{S}_s^0 := \{f \mid -f(-s) > p + Cs\}$ and $\mathscr{S}_t^T := \{f \mid f(T) - f(T-t) > q + Ct\}$. We also define the set of paths in the intersection of these events:

$$
\begin{aligned}
& \mathscr{S}^{0,T} := \{f \mid \exists s\geq 0 : -f(-s) > p + Cs; \exists t \geq 0 : f(T) - f(T-t) > q + Ct\} \\
& = \ \bigcup_{s\geq 0}\bigcup_{t\geq 0}\mathscr{S}_{s,t}^{0,T} = \mathscr{S}^0 \cap \mathscr{S}^T.
\end{aligned}
$$

Now let $X(t)$ satisfies Assumption 2.1 with $\alpha \in (1,2)$. Schilder's theorem combined with Theorem 4.1 entails the following result (as $B \to \infty$):

$$
-\frac{v(B)}{B^2}\log N(B) \to \inf_{f\in\mathscr{S}^{0,T}}\mathbb{I}(f) = \inf_{s\geq 0,t\geq 0}\left(\inf_{f\in\mathscr{S}_{s,t}^{0,T}}\mathbb{I}(f)\right) = \inf_{s\geq 0}\inf_{t\in[0,T)\cup\{T+s\}}\left(\inf_{f\in\mathscr{S}_{s,t}^{0,T}}\mathbb{I}(f)\right).
$$

Here $\mathbb{I}(f)$ is the rate function of a path f; for a detailed introduction and a formal framework, see e.g. [1, 3, 14]. The last equality is due to Lemma 3.1. Now consider the evaluation of the inner infimum (for fixed s, t). The key observation is that

$$\xi(s,t) := \inf_{f \in \mathscr{S}^{0,T}_{s,t}} \mathbb{I}(f) = -\lim_{n\to\infty} \frac{1}{n} \log \mathbb{P}\left(\frac{A(-s,0)}{\sqrt{n}} \geq p + Cs, \frac{A(T-t,T)}{\sqrt{n}} \geq q + Ct \right).$$

In other words: $\xi(s,t)$, for given $s, t \geq 0$, represents the large-deviations rate function of a bivariate Normally distributed random variable. Now [12, Exercise 4.1.9] can be applied, and three cases are to be distinguished:

- If $r(s,t) \geq \gamma(s,t)$ and $\sigma_Y^2(s) \leq \sigma_Z^2(t)$, then only the first requirement is 'tight' and $\xi(s,t)$ is independent of t:

$$\xi(s,t) = \frac{1}{2}\frac{1}{\sigma_Y^2(s)} = \frac{1}{2}\frac{(p+Cs)^2}{v(s)}. \tag{6}$$

- If $r(s,t) \geq \gamma(s,t)$ and $\sigma_Y^2(s) > \sigma_Z^2(t)$, then only the first requirement is 'tight' and $\xi(s,t)$ is independent of s:

$$\xi(s,t) = \frac{1}{2}\frac{1}{\sigma_Z^2(t)} = \frac{1}{2}\frac{(q+Ct)^2}{v(t)}. \tag{7}$$

- If $r(s,t) < \gamma(s,t)$, then, with $\Gamma(s,t) := \mathbb{C}\mathrm{ov}(A(-s,0), A(T-t,T))$, both requirements are 'tight':

$$\begin{aligned} \xi(s,t) &= \frac{1}{2}(p+Cs, q+Ct) \begin{pmatrix} v(s) & \Gamma(s,t) \\ \Gamma(s,t) & v(t) \end{pmatrix}^{-1} \begin{pmatrix} p+Cs \\ q+Ct \end{pmatrix} \\ &= \frac{1}{2}\frac{1}{1-r^2(s,t)}\left(\frac{(p+Cs)^2}{v(s)} - 2\frac{\Gamma(s,t)(p+Cs)(q+Ct)}{v(t)v(s)} + \frac{(q+Ct)^2}{v(t)} \right). \end{aligned} \tag{8}$$

Notice that the criterion $r(s,t) < \gamma(s,t)$ can be rewritten as

$$\frac{\Gamma(s,t)}{(p+Cs)(q+Ct)} < \min\{\sigma_Y^2(s), \sigma_Z^2(t)\}.$$

We thus retrieve

$$\lim_{B\to\infty} \frac{v(B)}{B^2} \log N(B) = -\inf_{s\geq 0} \inf_{t\in[0,T)\cup\{T+s\}} \xi_{\mathbb{B}_\alpha;1}(s,t).$$

5 Special cases

In this section we apply Theorem 4.1 to two special cases, viz.

- Gaussian input processes which possess a *short-range dependent* structure (SRD), by which we mean that $v(\cdot)$ is regularly varying with parameter $\alpha = 1$;
- Gaussian input processes which possess a *long-range dependent* structure (LRD), by which we mean that $v(\cdot)$ is regularly varying with parameter $\alpha \in (1, 2)$.

In particular, one could think of the following special cases which have been studied intensively in the literature. (i) *Integrated Gaussian processes*. In this case $X(t) = \int_0^t Z(s)\mathrm{d}s$, where $Z(\cdot)$ is a centered stationary Gaussian process with a continuous covariance function $R(t) := \mathbb{C}\mathrm{ov}(Z(s), Z(s+t)) > 0$. Note that if $\int_0^\infty R(v)\mathrm{d}v < \infty$, then

$$\mathbb{V}\mathrm{ar}(X(t)) = v(t) = 2\left(\int_0^\infty R(v)\mathrm{d}v\right) \cdot t(1+o(1))$$

as $t \to \infty$, and hence $X(\cdot)$ has an SRD structure. If $R(t)$ is regularly varying at ∞ with index $\alpha - 2$, for $\alpha \in (1,2)$, then $\mathbb{V}\mathrm{ar}(X(t))$ is regularly varying at ∞ with index α, which implies an LRD structure. (ii) *Fractional Brownian motions*. Then $X(t) = B_{\alpha/2}(t)$. Recall that for the case of $\alpha = 1$ we are in the SRD scenario, while $\alpha \in (1,2)$ corresponds to the LRD case.
The relevance of integrated Gaussian input processes in the theory of fluid models is discussed in e.g. [6, 7]; see also [5, 16]. The use of fractional Brownian motions in modelling input processes has been advocated by e.g. [18, 21].

5.1 The SRD case

In this section we focus on the class of input processes with a short range dependence structure, i.e., we assume that $\mathbb{V}\mathrm{ar}(X(t)) = v(t)$ is regularly varying at infinity with index $\alpha = 1$.

Proposition 5.1. *Assume that $\{X(t) : t \in \mathbb{R}\}$ satisfies Assumption 2.1 with $\alpha = 1$.*
(i) If $p > q > 0$, then

$$\lim_{B\to\infty} \frac{v(B)}{B^2} \log N(B) = -\begin{cases} 2pC & \text{if } T \le \frac{p-q}{C}; \\ 2pC + \frac{(CT+q-p)^2}{2T} & \text{if } \frac{p-q}{C} < T \le \frac{(\sqrt{p}+\sqrt{q})^2}{C}; \\ 2pC + 2qC & \text{if } T > \frac{(\sqrt{p}+\sqrt{q})^2}{C}. \end{cases} \tag{9}$$

(ii) If $p = q > 0$, then

$$\lim_{B\to\infty} \frac{v(B)}{B^2} \log N(B) = -\begin{cases} 2pC + \frac{C^2T}{2} & \text{if } T \le \frac{4p}{C}; \\ 4pC & \text{if } T > \frac{4p}{C}. \end{cases} \tag{10}$$

(iii) If $q > p > 0$, then

$$\lim_{B\to\infty} \frac{v(B)}{B^2} \log N(B) = -\begin{cases} 2qC & \text{if } T \le \frac{q-p}{C}; \\ 2pC + \frac{(CT+q-p)^2}{2T} & \text{if } \frac{q-p}{C} < T \le \frac{(\sqrt{p}+\sqrt{q})^2}{C}; \\ 2pC + 2qC & \text{if } T > \frac{(\sqrt{p}+\sqrt{q})^2}{C}. \end{cases} \tag{11}$$

Proof. By virtue of Theorem 4.1, we analyze

$$\inf_{s\ge0} \inf_{t\in[0,T)\cup\{T+s\}} \xi_{\mathbb{B}_1;1}(s,t) = \min\left\{\inf_{s\ge0}\inf_{t\in[0,T)} \xi_{\mathbb{B}_1;1}(s,t), \inf_{s\ge0} \xi_{\mathbb{B}_1;1}(s,s+T)\right\}.$$

Note that $r(s,t) \equiv 0$ for all $s \geq 0, t \in [0,T]$, and hence

$$\begin{aligned}\inf_{s\geq 0}\inf_{t\in[0,T)} \xi_{\mathbb{B}_1;1}(s,t) &= \inf_{s\geq 0}\inf_{t\in[0,T)} \frac{1}{2}\left(\frac{(p+Cs)^2}{s} + \frac{(q+Ct)^2}{t}\right) \\ &= 2pC + \frac{1}{2}\frac{(q+C\min\{T,q/C\})^2}{\min\{T,q/C\}}. \end{aligned} \tag{12}$$

Case (i): $p > q > 0$. It is convenient to split this scenario into two subcases: $T \leq (p-q)/C$ and $T > (p-q)/C$. Let us first consider $T \leq (p-q)/C$. This case follows from combining the fact that for each s,t,

$$\xi_{\mathbb{B}_1;1}(s,t) \geq \frac{1}{2\min\{\sigma_Y^2(s),\sigma_Z^2(t)\}} \geq \frac{1}{2\sigma_Y^2(s^\star)} = 2pC,$$

with $\xi_{\mathbb{B}_1;1}(s^\star, s^\star+T) = 2pC$ for $s^\star = p/C$. Then consider $T > (p-q)/C$. Let

$$\mathscr{S}_1 := \{s \geq 0 : \sigma_Y(s) \leq \sigma_Z(s+T)\}, \;\; \mathscr{S}_2 := \{s \geq 0 : \sigma_Y(s) > \sigma_Z(s+T)\}.$$

Note that $\{s \geq 0\} = \mathscr{S}_1 \cup \mathscr{S}_2$. Let us first analyze $\inf_{s\geq 0}\xi_{\mathbb{B}_1;1}(s,s+T)$. Note that for each $s \geq 0$

$$r(s,s+T) = r_{1,T}(s,t) < \gamma_{1,p,q}(s,s+T) = \gamma(s,s+T).$$

Indeed, for $s \in \mathscr{S}_1$ (using that $T > (p-q)/C$) we have

$$\gamma(s,s+T) - r(s,s+T) = \sqrt{\frac{s}{s+T}}\frac{CT+q-p}{p+Cs} > 0$$

while, for $s \in \mathscr{S}_2$, we have

$$\gamma(s,s+T) - r(s,s+T) = \sqrt{\frac{s}{s+T}}\left(\frac{(T+s)(p+Cs)}{s(q+C(s+T))} - 1\right) = \sqrt{\frac{s}{s+T}}\frac{Tp+s(p-q)}{s(q+C(s+T)} > 0.$$

Hence:

- if $s \in \mathscr{S}_1$, then

$$\xi_{\mathbb{B}_1;1}(s,s+T) = \frac{1}{2}\frac{(p+Cs)^2}{s} + \frac{1}{2}\frac{(CT+q-p)^2}{T};$$

- if $s \in \mathscr{S}_2$, then

$$\xi_{\mathbb{B}_1;1}(s,s+T) = \frac{1}{2}\frac{(q+C(T+s))^2}{T+s} + \frac{1}{2}\frac{(pT+s(p-q))^2}{sT(s+T)} = \frac{1}{2}\frac{(p+Cs)^2}{s} + \frac{1}{2}\frac{(CT+q-p)^2}{T}.$$

The above implies that

$$\inf_{s\geq 0}\xi_{\mathbb{B}_1;1}(s,s+T) = \inf_{s\geq 0}\frac{1}{2}\frac{(p+Cs)^2}{s} + \frac{1}{2}\frac{(CT+q-p)^2}{T} = 2pC + \frac{1}{2}\frac{(CT+q-p)^2}{T}. \tag{13}$$

Finally, in order to complete the proof of (i), it suffices to check that combination of (12) with (13) leads to

$$\inf_{s\geq 0}\xi_{\mathbb{B}_1;1}(s,s+T) \leq \inf_{s\geq 0}\inf_{t\in[0,T)}\xi_{\mathbb{B}_1;1}(s,t) \quad \text{for} \quad \frac{p-q}{C} < T \leq \frac{(\sqrt{p}+\sqrt{q})^2}{C},$$

$$\inf_{s\geq 0}\xi_{\mathbb{B}_1;1}(s,s+T) \geq \inf_{s\geq 0}\inf_{t\in[0,T)}\xi_{\mathbb{B}_1;1}(s,t) \quad \text{for} \quad T > \frac{(\sqrt{p}+\sqrt{q})^2}{C}.$$

Case (ii): $p = q > 0$. This case follows from the same arguments as used in case (i). We omit the details.
Case (iii): $q > p > 0$. Analogously to case (i) we separately analyze the scenarios $T \le q - p/C$ and $T > (q-p)/C$. First consider $T \le (q-p)/C$. The result directly follows from

$$\xi_{\mathbb{B}_1;1}(s,t) \ge \frac{1}{2\min\{\sigma_Y^2(s), \sigma_Z^2(t)\}} \ge \frac{1}{2\sigma_Z^2(t^\star)} = 2qC,$$

for each s, t, in conjunction with $\xi_{\mathbb{B}_1;1}(t^\star - T, t^\star) = 2qC$ for $t^\star = q/C$. Then focus on $T > (q-p)/C$. Let

$$\mathscr{S}_{21} := \{s \ge 0 : \sigma_Y(s) > \sigma_Z(s+T), r(s, s+T) < \gamma(s, s+T)\},$$

$$\mathscr{S}_{22} := \{s \ge 0 : \sigma_Y(s) > \sigma_Z(s+T), r(s, s+T) \ge \gamma(s, s+T)\}.$$

We analyze $\inf_{s\ge 0} \xi_{\mathbb{B}_1;1}(s, s+T)$.

- If $s \in \mathscr{S}_1$, then

  $$r(s, s+T) = \sqrt{\frac{s}{s+T}} < \sqrt{\frac{s}{s+T}}\frac{C(s+T)+q}{p+Cs} = \gamma(s, s+T),$$

  and therefore

  $$\xi_{\mathbb{B}_1;1}(s, s+T) = \frac{1}{2}\frac{(p+Cs)^2}{s} + \frac{1}{2}\frac{(CT+q-p)^2}{T}. \tag{14}$$

- If $s \in \mathscr{S}_{21}$, then standard calculation leads to the same formula as in (14), i.e.,

  $$\xi_{\mathbb{B}_1;1}(s, s+T) = \frac{1}{2}\frac{(q+C(T+s))^2}{T+s} + \frac{1}{2}\frac{(pT+s(p-q))^2}{sT(s+T)} = \frac{1}{2}\frac{(p+Cs)^2}{s} + \frac{1}{2}\frac{(CT+q-p)^2}{T}. \tag{15}$$

  Hence, using that $p/C \in \mathscr{S}_{21}$, we have

  $$\inf_{s\in\mathscr{S}_1\cup\mathscr{S}_{21}} \xi_{\mathbb{B}_1;1}(s, s+T) = 2pC + \frac{1}{2}\frac{(CT+q-p)^2}{T}. \tag{16}$$

- If $s \in \mathscr{S}_{22}$, then

  $$\xi_{\mathbb{B}_1;1}(s, s+T) = \frac{1}{2\min\{\sigma_Y^2(s), \sigma_Z^2(s+T)\}} = \frac{(q+C(s+T))^2}{2(s+T)}. \tag{17}$$

  Moreover, the fact that $s \in \mathscr{S}_{22}$ implies

  $$r(s, s+T) \ge \gamma(s, s+T) \Leftrightarrow s \ge \frac{pT}{q-p}.$$

  We conclude that

  $$\inf_{s\in\mathscr{S}_{22}} \xi_{\mathbb{B}_1;1}(s, s+T) = \xi_{\mathbb{B}_1;1}\left(\frac{pT}{q-p}, \frac{pT}{q-p} + T\right) = \frac{1}{2}\frac{q(CT+q-p)^2}{(q-p)T}. \tag{18}$$

The comparison of (16) with (18) now implies that

$$\inf_{s\ge 0} \xi_{\mathbb{B}_1;1}(s, s+T) = 2pC + \frac{1}{2}\frac{(CT+q-p)^2}{T}. \tag{19}$$

Analogously to the proof of (i), the combination of (12) with (19) completes the proof. □

Remark 5.2. Related results for queues fed by Brownian motion have recently been obtained in [11]. There also emphasis was put on the nature of the decay rates, and the shape of the *most likely path* towards the rare event [1, 12]. In accordance with Prop. 5.1, it was found that for T up to some threshold, the decay rate of the joint probability equals the decay rate of $\mathbb{P}(Q > \max\{p,q\}B)$, with Q denoting the steady-state workload: if $p > q$ then $\{Q_0 > pB\}$ essentially implies $\{Q_{TB} > qB\}$ for T small, and if $p < q$ then $\{Q_{TB} > qB\}$ essentially implies $\{Q_0 > pB\}$ for T small — this is regime (A), as it was mentioned in the introduction. Then there is an intermediate range of values of T, regime (B), in which the event of interest is roughly equal to

$$\{Q_0 > pB, A(0,TB) \geq qB + cT - pB\};$$

in this range the buffer does not become empty between 0 and TB. For large T (regime (C)) the most likely scenario is that the queue reaches level pB at time 0, drains, and starts building up just before TB, to reach value qB at TB. In the Brownian case the most likely path of this scenario consists of two independent busy periods.

5.2 The LRD case

In this subsection we focus on the scenario $\alpha \in (1,2)$. Whereas for the case of $\alpha = 1$ we could rely on explicit computations, for $\alpha \in (1,2)$ the analysis of the rate function

$$\inf_{s\geq 0}\inf_{t\in[0,T)\cup\{T+s\}} \xi_{\mathbb{B}_\alpha;1}(s,t)$$

turns out to be substantially harder. Before presenting the main results of this section, we introduce some additional notation. Define, for a given $\alpha \in (1,2)$, and $p,q,C > 0$,

$$s^\star := \arg\max_{s\geq 0}\left\{\frac{s^{\alpha/2}}{p+Cs}\right\} = \frac{p}{C}\frac{\alpha}{2-\alpha},$$

$$t^\star := \arg\max_{t\geq 0}\left\{\frac{t^{\alpha/2}}{q+Cs}\right\} = \frac{q}{C}\frac{\alpha}{2-\alpha},$$

and

$$R(x) := \frac{1}{2}\left(\frac{2x}{2-\alpha}\right)^{2-\alpha}\left(\frac{2C}{\alpha}\right)^{\alpha}.$$

Note that for $X(t) \equiv \mathbb{B}_\alpha(t)$ we have that

$$\max_{s\geq 0}\mathbb{V}\mathrm{ar}(Y_1(s)) = \mathbb{V}\mathrm{ar}(Y_1(s^\star)) = \frac{1}{2R(p)},\quad \max_{t\geq 0}\mathbb{V}\mathrm{ar}(Z_1(t)) = \mathbb{V}\mathrm{ar}(Z_1(t^\star)) = \frac{1}{2R(q)}.$$

The following general bounds hold. The upper bound in (20) essentially says that the decay rate of the joint probability is smaller than the decay rate of the least likely event; the lower bound in (20) says that the joint probability is larger than the product of the individual probabilities (which makes sense in view of the positive correlation).

Proposition 5.3. *Assume that* $\{X(t) : t \in \mathbb{R}\}$ *satisfies Assumption* 2.1 *with* $\alpha \in (1,2)$. *Then*

$$-\max\{R(p),R(q)\} \geq \lim_{B\to\infty}\frac{v(B)}{B^2}\log N(B) > -(R(p)+R(q)). \tag{20}$$

Proof. The upper bound follows immediately from

$$\begin{aligned}\inf_{s\ge 0}\inf_{t\in[0,T)\cup\{T+s\}}\xi_{\mathbb{B}_\alpha;1}(s,t) &\ge \inf_{s\ge 0}\inf_{t\ge 0}\xi_{\mathbb{B}_\alpha;1}(s,t)\\ = &\inf_{s\ge 0,t\ge 0}\frac{1}{2}\frac{1}{\min\{\sigma_Y^2(s),\sigma_Z^2(t)\}}\left(1+\frac{(\gamma(s,t)-r(s,t))^2}{1-r^2(s,t)}I(s,t)\right)\\ \ge &\max\left\{\inf_{s\ge 0}\frac{(p+Cs)^2}{2v(s)},\inf_{t\ge 0}\frac{(q+Ct)^2}{2v(t)}\right\}=\max\{R(p),R(q)\}.\end{aligned}$$

The lower bound is due to the fact that, due to Lemma 4.5, for some $\overline{\varepsilon}>\underline{\varepsilon}>0$,

$$\begin{aligned}\inf_{s\ge 0}\inf_{t\in[0,T)\cup\{T+s\}}\xi_{\mathbb{B}_\alpha;1}(s,t) &= \min_{s\in[\underline{\varepsilon},\overline{\varepsilon}]}\min_{t\in[\underline{\varepsilon},T)\cup\{T+s\}}\xi_{\mathbb{B}_\alpha;1}(s,t)\\ = &\min_{s\in[\underline{\varepsilon},\overline{\varepsilon}]}\min_{t\in[\underline{\varepsilon},T)\cup\{T+s\}}\frac{1}{2}\frac{1}{\min\{\sigma_Y^2(s),\sigma_Z^2(t)\}}\left(1+\frac{(\gamma(s,t)-r(s,t))^2}{1-r^2(s,t)}I(s,t)\right).\end{aligned}\tag{21}$$

Moreover the assumption that $\alpha>1$ straightforwardly implies $r(s,t)>0$. Hence

$$\frac{(\gamma(s,t)-r(s,t))^2}{1-r^2(s,t)}<\gamma^2(s,t)$$

for each $s,t>0$, and therefore (21) is majorized by

$$\begin{aligned}&\min_{s\in[\underline{\varepsilon},\overline{\varepsilon}]}\min_{t\in[\underline{\varepsilon},T)\cup\{T+s\}}\frac{1}{2}\frac{1}{\min\{\sigma_Y^2(s),\sigma_Z^2(t)\}}\left(1+\gamma^2(s,t)\right)\\ = &\min_{s\in[\underline{\varepsilon},\overline{\varepsilon}]}\min_{t\in[\underline{\varepsilon},T)\cup\{T+s\}}\frac{1}{2}\left(\frac{1}{\sigma_Y^2(s)}+\frac{1}{\sigma_Z^2(t)}\right)=R(p)+R(q).\end{aligned}$$

This completes the proof. □

In the following we determine the values of T for which the lower bound in (20) is tight.

Proposition 5.4. *Assume that $\{X(t):t\in\mathbb{R}\}$ satisfies Assumption 2.1 with $\alpha\in(1,2)$.*
(i) If $p>q>0$, then there exists a unique $T^\star$ solving the equation

$$\gamma(s^\star,s^\star+T^\star) \quad = \quad r(s^\star,s^\star+T^\star)\tag{22}$$

such that

$$\lim_{B\to\infty}\frac{v(B)}{B^2}\log N(B)=-R(p) \text{ for } T\le T^\star;\quad \lim_{B\to\infty}\frac{v(B)}{B^2}\log N(B)<-R(p) \text{ for } T>T^\star.$$

(ii) If $q>p>0$, then there exists a unique $T_\star$ solving the equation

$$\gamma(t^\star-T_\star,t^\star) \quad = \quad r(t^\star-T_\star,t^\star)\tag{23}$$

such that

$$\lim_{B\to\infty}\frac{v(B)}{B^2}\log N(B)=-R(q) \text{ for } T\le T_\star;\quad \lim_{B\to\infty}\frac{v(B)}{B^2}\log N(B)<-R(q) \text{ for } T>T_\star.$$

Proof. First consider the case $p>q>0$. Note that in order to have

$$\lim_{B\to\infty}\frac{v(B)}{B^2}\log N(B)=-R(p)$$

we need the following two conditions to be satisfied:

$$\begin{aligned} \gamma(s^\star, s^\star + T) &\leq r(s^\star, s^\star + T) && (24)\\ \sigma_Y(s^\star) &\leq \sigma_Z(s^\star + T). && (25) \end{aligned}$$

Under (25) we have

$$\begin{aligned} r(s^\star, s^\star + T) &= \frac{(T + s^\star)^\alpha - T^\alpha + (s^\star)^\alpha}{2(s^\star(s^\star + T))^{\alpha/2}} = \frac{1}{2}\left(\frac{s^\star}{s^\star + T}\right)^{\alpha/2}\left(\left(\frac{T + s^\star}{s^\star}\right)^\alpha - \left(\frac{T}{s^\star}\right)^\alpha + 1\right);\\ \gamma(s^\star, s^\star + T) &= \left(\frac{s^\star}{s^\star + T}\right)^{\alpha/2}\frac{q + C^\star + CT}{p + Cs^\star} = \left(\frac{s^\star}{s^\star + T}\right)^{\alpha/2}\left(1 + \frac{q - p}{p + Cs^\star} + \frac{Cs^\star}{p + Cs^\star}\frac{T}{s^\star}\right). \end{aligned}$$

Noticing that

$$\frac{Cs^\star}{p + Cs^\star} = \alpha/2; \quad -1 < \frac{q - p}{p + Cs^\star} = \frac{q - p}{p}\left(1 - \frac{\alpha}{2}\right) < 0,$$

Inequalities (24) and (25) are equivalent to respectively

$$1 + 2\frac{q - p}{p}(1 - \alpha/2) + \alpha\frac{T}{s^\star} \leq \left(1 + \frac{T}{s^\star}\right)^\alpha - \left(\frac{T}{s^\star}\right)^\alpha, \tag{26}$$

$$1 + \frac{q - p}{p}(1 - \alpha/2) + \frac{\alpha}{2}\frac{T}{s^\star} \leq \left(1 + \frac{T}{s^\star}\right)^{\alpha/2}. \tag{27}$$

Interestingly, however, we have that Inequality (26) implies Inequality (27). This can be shown as follows. First rewrite Inequality (26) to

$$1 + \frac{q - p}{p}(1 - \alpha/2) + \frac{\alpha}{2}\frac{T}{s^\star} \leq \frac{1}{2}\left(1 + \left(1 + \frac{T}{s^\star}\right)^\alpha - \left(\frac{T}{s^\star}\right)^\alpha\right). \tag{28}$$

Let $\check{X}(t)$ correspond to fBm with variance curve $v(t) = t^\alpha$, and let $\check{A}(s,t) := \check{X}(t) - \check{X}(s)$. Then

$$\begin{aligned} \frac{\mathbb{C}\text{ov}(\check{A}(0, s^\star), \check{A}(0, s^\star + T))}{\mathbb{V}\text{ar}(\check{A}(0, s^\star))} &= \frac{1}{2}\left(1 + \left(1 + \frac{T}{s^\star}\right)^\alpha - \left(\frac{T}{s^\star}\right)^\alpha\right);\\ \sqrt{\frac{\mathbb{V}\text{ar}(\check{A}(0, s^\star + T))}{\mathbb{V}\text{ar}(\check{A}(0, s^\star))}} &= \left(1 + \frac{T}{s^\star}\right)^{\alpha/2}. \end{aligned}$$

Consequently, using the fact that the correlation coefficient is smaller than 1,

$$\begin{aligned} 0 &< \frac{1}{2}\left(1 + \left(1 + \frac{T}{s^\star}\right)^\alpha - \left(\frac{T}{s^\star}\right)^\alpha\right) \Big/ \left(1 + \frac{T}{s^\star}\right)^{\alpha/2}\\ &= \frac{\mathbb{C}\text{ov}(\check{A}(0, s^\star), \check{A}(0, s^\star + T))}{\sqrt{\mathbb{V}\text{ar}(\check{A}(0, s^\star + T))\mathbb{V}\text{ar}(\check{A}(0, s^\star))}} = \mathbb{C}\text{orr}(\check{A}(0, s^\star), \check{A}(0, s^\star + T)) < 1. \end{aligned}$$

Hence the right-hand side of Inequality (28) is smaller then the right-hand side of Inequality (27), and we indeed have that Inequality (26) implies Inequality (27).
Now it suffices to show that the functions

$$f(x) := (1 + x)^\alpha - x^\alpha \ \text{ and } \ g(x) := 1 + 2\left(1 - \frac{\alpha}{2}\right)\frac{q - p}{p} + \alpha x$$

intersect in a unique point $x^\star > 0$. Indeed the function $g(\cdot)$ is increasing and

$$g(0) = 1 + (2-\alpha)\frac{q-p}{p} < 1 = f(0).$$

Now notice that $f(\cdot)$ is increasing and concave, since $f'(x) = \alpha((1+x)\alpha - 1 - x^{\alpha-1}) > 0$ and $f''(x) = \alpha(\alpha-1)((1+x)^{\alpha-2} - x^{\alpha-2}) < 0$. Then the graphs of the two functions must intersect in a unique point $x^\star > 0$. We have thus found that there exists a unique $T^\star \geq 0$ such that for all $T \leq T^\star$ we have that Inequality (24) is satisfied.
Since the idea of the proof for the case $q > p > 0$ is analogous to the proof for the case $p > q > 0$, we omit the details. □

In the next proposition we give a lower bound on $T^\star$ and $T_\star$.

Proposition 5.5. *(i) If $p > q > 0$, then $T^\star \geq (p-q)/C$. (ii) If $q > p > 0$, then $T_\star \geq (q-p)/C$.*

Proof. Since the proofs of (i) and (ii) are analogous, we focus on the argument that shows (i). We need to check whether $T = (p-q)/C$ satisfies (24).
First notice that (under the notation used in the proof of Proposition 5.4)

$$g\left(\frac{p-q}{Cs^\star}\right) = 1 + 2\frac{q-p}{p+Cs^\star} + \alpha\frac{p-q}{C^\star} = 1$$

and we have that $f(x)$ and $g(x)$ are increasing and $f(0) = 1$. Hence we have

$$f\left(\frac{p-q}{Cs^\star}\right) \geq f(0) = g\left(\frac{p-q}{Cs^\star}\right).$$

This proves the claim in part (i). □

Remark 5.6. Conditions $T < T^\star$ and $T < T_\star$ have interesting interpretations. Consider for instance $T < T^\star$. Elementary computations with the conditional distribution of Normal random variables yield that $T < T^\star$ is equivalent to

$$\mathbb{E}(A(0,T) \mid A(-s^\star, 0) = p + cs^\star) \geq q - p + cT.$$

The interpretation is that, given the queue exceeds pB at 0, exceeding qB at time TB is not a rare event anymore. A similar interpretation can be given to condition $T < T_\star$.

Prop. 5.4 says that, just as in the SRD case, if and only if T is smaller than some threshold, then the decay rate of the joint probability equals the decay rate of $\mathbb{P}(Q > \max\{p,q\}B)$, with Q denoting the steady-state workload. In other words: $T^\star$ (in case $p > q$) or $T_\star$ (in case $p < q$) separates regime (A) from regime (B). In the SRD case, we found a second threshold, separating regime (B) from regime (C): below this threshold the buffer does not become empty (most likely) before time TB, and above it it *does* (for large values of T). In the LRD case we believe that this structure still applies, but we have been able to prove just a partial result, which is stated in Prop. 5.8. It says that for T large enough, we are in Regime (C).

Lemma 5.7.

$$\inf_{s\geq 0} \xi_{\mathbb{B}_\alpha}(s, T+s) \geq \frac{1}{2}C^2T^{2-\alpha}.$$

Proof. Uniformly in $s \geq 0$,

$$\xi_{\mathbb{B}_\alpha}(s, T+s) \geq \frac{1}{2}\frac{(q + C(T+s))^2}{(T+s)^\alpha} \geq \frac{1}{2}C^2 T^{2-\alpha}.$$

This proves the stated. □

Due to Prop. 5.3, for $\alpha \in (1, 2)$, we have

$$\inf_{s \geq 0} \inf_{t \in [0,T) \cup \{T+s\}} \xi_{\mathbb{B}_\alpha}(s, t) \leq \xi^\star := R(p) + R(q).$$

Upon combining the above, we obtain the following result. On an intuitive level, it says that for T larger than some explicitly given threshold, with overwhelming probability the most likely path is such that the busy period in which 0 is contained does not coincide with the busy period in which T is contained.

Proposition 5.8. *For*

$$T > T^\sharp := \left(\frac{2\xi^\star}{C^2}\right)^{1/(2-\alpha)}$$

we have that

$$\lim_{B \to \infty} \frac{v(B)}{B^2} \log N(B) = \inf_{s \geq 0} \inf_{t \in [0,T)} \xi_{\mathbb{B}_\alpha}(s, t).$$

6 Discussion and concluding remarks

This paper analyzed the logarithmic asymptotics of $\mathbb{P}(Q_0 > pB, Q_{TB} > qB)$. We have identified the corresponding decay rate. An open issue concerns the *exact* asymptotics, i.e., can we find an explicit function $\varphi(\cdot)$ such that

$$\mathbb{P}(Q_0 > pB, Q_{TB} > qB) \cdot \varphi(B) \to 1$$

as $B \to \infty$? It is noted that for the single-dimensional case this was already a highly non-trivial task [10, 15, 17], and the answer involves the so-called *Pickands constant*.

Then we considered the above decay rate in more detail, and identified three regimes for T. The SRD case could be dealt with explicitly, in that we presented closed-form expressions for the decay rate, as well as for the critical values of T that separate regime (A) from regime (B), and regime (B) from regime (C). In the LRD case we found an explicit expression for the decay rate in regime (A), and we showed that the critical value of T, which we called $T^\star$ for $p > q$ and $T_\star$ for $p < q$, that separates regime (A) from regime (B) is the solution to some algebraic equation. In addition we showed that for T larger than some explicitly given number $T^\sharp$, we are in regime (C). This in principle still allows oscillations between regimes (B) and (C) in the region between $T^\star$ ($T_\star$, respectively) and $T^\sharp$. We conjecture that such oscillations do not occur.

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