Concentration and Deviation Inequalities in Infinite Dimensions via Covariance Representations

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Abstract

Concentration and deviation inequalities are obtained for functionals on Wiener space, Poisson space or more generally for normal martingales and binomial processes. The method used here is based on covariance identities obtained via the chaotic representation property, and provides an alternative to the use of logarithmic Sobolev inequalities. It allows to recover known concentration and deviation inequalities on the Wiener and Poisson space (including the ones given by sharp logarithmic Sobolev inequalities), and extends results available in the discrete case, i.e. on the infinite cube $\{-1,1\}^\infty$.

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1 Introduction

The purpose of the present paper is to further explore topics in concentration and deviation inequalities, in particular in infinite dimensional settings. Deviation and concentration have attracted a lot of attention in recent years well summarized in [17, 18] where the reader will find up-to-date information, precise references and credit.

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Among the various methods used to obtain these results one that we would like to emphasize is based on covariance representations. In particular, it was used in the Gaussian or more generally infinitely divisible cases in [4], [13]. Here we tackle the infinite dimensional case with a similar method, recovering the results recently obtained in [2], [6], using (modified) logarithmic Sobolev inequalities, and also the stronger results of [30] obtained from sharp logarithmic Sobolev inequalities, cf. Corollaries 4.3 and 5.1. We also show that our method covers the discrete case and carries the concentration inequalities of [6] to infinite dimensions, cf. Proposition 7.8 and Corollary 7.7. The content of this paper is as follows. In the next section, we briefly review the notion of normal martingale and recall elements of its structure theory. Section 3 is devoted to concentration inequalities for normal martingales having the chaos representation property. This is then specialized to "deterministic" structure equations that simultaneously cover the Poisson and Wiener cases in Section 4. The general case of Poisson random measure on a metric space is treated in Section 5, and the gradient of [8] is also used in Section 6 for the Poisson process on $\mathbb{R}_+$. Section 7 is devoted to the case of the binomial process, and it includes functionals on the infinite discrete cube under non-symmetric Bernoulli measures.

2 Preliminaries: normal martingales

Let $(M_t)_{t\in\mathbb{R}_+}$ be a normal martingale, i.e. $(M_t)_{t\in\mathbb{R}_+}$ is a martingale with deterministic angle bracket $d\langle M_t, M_t\rangle = dt$. Let $(\mathcal{F}_t)_{t\in\mathbb{R}_+}$ be the filtration generated by $(M_t)_{t\in\mathbb{R}_+}$ and let $\mathcal{F} = \bigvee_{t\in\mathbb{R}^+} \mathcal{F}_t$. The multiple stochastic integral $I_n(f_n)$ is then defined as

$$I_n(f_n) = n! \int_0^\infty \int_0^{t_n} \cdots \int_0^{t_2} f_n(t_1,\ldots,t_n) dM_{t_1}\cdots dM_{t_n}, \quad f_n \in L^2(\mathbb{R}_+)^{\circ n}, \quad n \geq 1,$$

where $L^2(\mathbb{R}_+)^{\circ n}$ is the set of symmetric square integrable functions on $\mathbb{R}_+^n$, with

$$E[I_n(f_n)I_m(g_m)] = n!\mathbf{1}_{\{n=m\}}\langle f_n, g_m\rangle_{L^2(\mathbb{R}_+)^{\circ n}}. \tag{2.1}$$

We assume that $(M_t)_{t\in\mathbb{R}_+}$ has the chaos representation property, i.e. every $F \in L^2(\Omega,\mathcal{F},P)$ has a decomposition as $F = \sum_{n=0}^\infty I_n(f_n)$. Let $D : \mathrm{Dom}(D) \longrightarrow L^2(\Omega \times$

$\mathbb{R}_+, dP \times dt)$ denote the closable gradient operator defined as

$$D_t F = \sum_{n=1}^{\infty} n I_{n-1}(f_n(*, t)), \quad dP \times dt - a.e.,$$

with $F = \sum_{n=0}^{\infty} I_n(f_n)$. The Clark formula is a consequence of the chaos representation property for $(M_t)_{t\in\mathbb{R}_+}$, and states that any $F \in \mathrm{Dom}(D) \subset L^2(\Omega, \mathcal{F}, P)$ has a representation

$$F = E[F] + \int_0^{\infty} E[D_t F \mid \mathcal{F}_t] dM_t. \tag{2.2}$$

It admits a simple proof via the chaos expansion of F:

$$\begin{aligned} F &= E[F] + \sum_{n=1}^{\infty} n! \int_0^{\infty} \int_0^{t_n} \cdots \int_0^{t_2} f_n(t_1, \ldots, t_n) dM_{t_1} \cdots dM_{t_n} \\ &= E[F] + \sum_{n=1}^{\infty} n \int_0^{\infty} I_{n-1}(f_n(*, t_n) \mathbf{1}_{\{* < t_n\}}) dM_{t_n} = E[F] + \int_0^{\infty} E[D_t F \mid \mathcal{F}_t] dM_t. \end{aligned}$$

Let $(P_t)_{t\in\mathbb{R}_+}$ denote the Ornstein-Uhlenbeck semi-group, defined as

$$P_t F = \sum_{n=0}^{\infty} e^{-nt} I_n(f_n),$$

with $F = \sum_{n=0}^{\infty} I_n(f_n)$.

Proposition 2.1 *Let $F, G \in \mathrm{Dom}(D)$. Then*

$$\mathrm{Cov}(F, G) = E\left[\int_0^{\infty} D_t F E[D_t G \mid \mathcal{F}_t] dt\right], \tag{2.3}$$

and

$$\mathrm{Cov}(F, G) = E\left[\int_0^{\infty} \int_0^{\infty} e^{-s} D_u F P_s D_u G du ds\right]. \tag{2.4}$$

Proof. The first identity is a consequence of the Clark formula. By orthogonality of multiple integrals of different orders and continuity of P_s on $L^2(\Omega)$, it suffices to prove the second identity for $F = I_n(f_n)$ and $G = I_n(g_n)$. But

$$\begin{aligned} E[I_n(f_n) I_n(g_n)] &= n! \langle f_n, g_n \rangle_{L^2(\mathbb{R}_+^n)} = \frac{1}{n} E\left[\int_0^{\infty} D_u F D_u G du\right] \\ &= E\left[\int_0^{\infty} e^{-s} \int_0^{\infty} D_u F P_s D_u G du ds\right]. \end{aligned}$$

□

Relation (2.4) implies the covariance inequality

$$|\mathrm{Cov}(F,G)| \leq \|DF\|_{L^\infty(\Omega,L^2(\mathbb{R}_+))} E[\|DG\|_{L^2(\mathbb{R}_+)}]. \tag{2.5}$$

If $(M_t)_{t\in\mathbb{R}_+}$ is in $L^4(\Omega,\mathcal{F},P)$ then the chaos representation property implies that there exists a square-integrable predictable process $(\phi_t)_{t\in\mathbb{R}_+}$ such that

$$d[M_t,M_t] = dt + \phi_t dM_t, \quad t \in \mathbb{R}_+. \tag{2.6}$$

This last equation is called a structure equation, cf. [11]. Let $i_t = \mathbf{1}_{\{\phi_t=0\}}$ and $j_t = 1-i_t = \mathbf{1}_{\{\phi_t\neq 0\}}$, $t\in\mathbb{R}_+$. The continuous part of $(M_t)_{t\in\mathbb{R}_+}$ is given by $dM_t^c = i_t dM_t$ and the eventual jump of $(M_t)_{t\in\mathbb{R}_+}$ at time $t\in\mathbb{R}_+$ is given by $\Delta M_t = \phi_t$ on $\{\Delta M_t \neq 0\}$, $t\in\mathbb{R}_+$, see [11], p. 70. The following are examples of normal martingales with the chaos representation property, cf. [11].

a) $(\phi_t)_{t\in\mathbb{R}_+}$ is deterministic. Then $(M_t)_{t\in\mathbb{R}_+}$ can be represented as

$$dM_t = i_t dB_t + \phi_t(dN_t - \lambda_t dt), \quad t\in\mathbb{R}_+, \quad M_0 = 0, \tag{2.7}$$

with $\lambda_t = (1-i_t)/\phi_t^2$, $t\in\mathbb{R}_+$, where $(B_t)_{t\in\mathbb{R}_+}$ is a standard Brownian motion, and $(N_t)_{t\in\mathbb{R}_+}$ a Poisson process independent of $(B_t)_{t\in\mathbb{R}_+}$, with intensity $\nu_t = \int_0^t \lambda_s ds$, $t\in\mathbb{R}_+$.

b) Azéma martingales where $\phi_t = \beta M_t$, $\beta\in[-2,0)$.

If $(\phi_t)_{t\in\mathbb{R}_+}$ is a deterministic function, then $i_t D_t$ is still a derivation operator, and we have the product rule

$$D_t(FG) = FD_tG + GD_tF + \phi_t D_tF D_tG, \quad t\in\mathbb{R}_+, \tag{2.8}$$

cf. Proposition 1.3 of [25]. In fact D_t can be written as

$$D_t = \frac{j_t}{\phi_t}\Delta_t^\phi + i_t D_t, \tag{2.9}$$

where Δ_t^ϕ is the finite difference operator defined on random functionals by addition at time t of a jump of height ϕ_t to $(M_t)_{t\in\mathbb{R}_+}$. If $\phi_t \neq 0$, this implies

$$D_t e^F = \frac{e^F}{\phi_t}(e^{\phi_t D_t F} - 1), \tag{2.10}$$

and at the limit $\phi_t \to 0$, D_t becomes a derivation: $D_t e^F = e^F D_t F$.
In the deterministic case, an Ornstein-Uhlenbeck process $(X_t)_{t\in\mathbb{R}_+}$ can be associated with the semi-group $(P_s)_{s\in\mathbb{R}_+}$, and this implies the continuity of P_s.

Lemma 2.2 *Assume that $(\phi_t)_{t\in\mathbb{R}_+}$ is a deterministic function. For $F \in \mathrm{Dom}(D)$ we have*

$$\|P_t DF\|_{L^\infty(\Omega,L^2(\mathbb{R}_+))} \le \|DF\|_{L^\infty(\Omega,L^2(\mathbb{R}_+))}, \quad t \in \mathbb{R}_+. \tag{2.11}$$

Proof. Let $(M_t)_{t\in\mathbb{R}_+}$ be defined as in (2.7) on the product space $\Omega = \Omega_1 \times \Omega_2$ of independent Brownian motion $(B_t)_{t\in\mathbb{R}_+}$ and Poisson process $(N_t)_{t\in\mathbb{R}_+}$. The exponential vector

$$\varepsilon(f) = \sum_{n=0}^\infty \frac{1}{n!} I_n(f^{\circ n}),$$

$f \in L^1(\mathbb{R}_+) \cap L^2(\mathbb{R}_+)$, has the probabilistic interpretation

$$\varepsilon(f) = \exp\left(\int_0^\infty i_s f(s) dB(s) + \int_0^\infty j_s \log(1+\phi(s)f(s)) dN(s) \right.$$
$$\left. -\frac{1}{2}\int_0^\infty i_s f(s) ds - \int_0^\infty j_s \frac{f(s)}{\phi(s)} ds \right).$$

Let $(X_1^t)_{t\in\mathbb{R}_+}$ and $(X_2^t)_{t\in\mathbb{R}_+}$ be respectively the classical Ornstein-Uhlenbeck process on Wiener space, and the Ornstein-Uhlenbeck process on Poisson space [29]. We have

$$\begin{aligned}
&E[\varepsilon(f)(X_1^t, X_2^t) \mid (X_1^0, X_2^0)] \\
&= E\left[\exp\left(\int_0^\infty i_s f(s) dX_1^t(s) + \int_0^\infty j_s \log(1+\phi(s)f(s)) dX_2^t(s)\right.\right. \\
&\qquad \left.\left. -\frac{1}{2}\int_0^\infty i_s f(s) ds - \int_0^\infty j_s \frac{f(s)}{\phi(s)} ds \right) \mid (X_1(0), X_2(0))\right] \\
&= \exp\left(\int_0^\infty i_s e^{-t} f(s) dX_1^0(s) + \int_0^\infty j_s \log(1+e^{-t}\phi(s)f(s)) dX_2^0(s)\right. \\
&\qquad \left. -\frac{1}{2}\int_0^\infty i_s e^{-t} f(s) ds - \int_0^\infty j_s e^{-t} \frac{f(s)}{\phi(s)} ds \right). \\
&= \varepsilon(e^{-t} f)(X_1^0, X_2^0) = P_t \varepsilon(f).
\end{aligned}$$

This identity extends to linear combinations of exponential vectors by linearity, and to $L^2(\Omega)$ by density and continuity of P_t. This implies that

$$\|P_t DF\|_{L^\infty(\Omega,L^2(\mathbb{R}_+))} \le \|P_t |DF|_{L^2(\mathbb{R}_+)}\|_{L^\infty(\Omega)} \le \|DF\|_{L^\infty(\Omega,L^2(\mathbb{R}_+))}, \quad t \in \mathbb{R}_+,$$

for all $F \in \mathrm{Dom}(D)$. □

Before proceeding to general concentration inequalities for normal martingales with the chaos representation property, we note that some infinite dimensional inequalities can be obtained from their finite dimensional analogues. For example if $(M_t)_{t\in\mathbb{R}_+}$ is a standard Brownian motion, then D is a derivation operator whose action on cylindrical functionals of the form $F = f(I_1(e_1),\dots,I_1(e_n))$, $e_1,\dots,e_n \in L^2(\mathbb{R}_+)$, f bounded and $\mathcal{C}^1$ on $\mathbb{R}^n$, is given by

$$D_t F = \sum_{i=1}^{i=n} e_i(t)\partial_i f(I_1(e_1),\dots,I_1(e_n)), \quad t \in \mathbb{R}_+.$$

We also have the relations

$$\|DF\|_{L^2(\mathbb{R}_+)} = |\nabla f|(I_1(e_1),\dots,I_1(e_n)), \quad a.s.,$$

and

$$\|DF\|_{L^\infty(\Omega,L^2(\mathbb{R}_+))} = \|f\|_{\mathrm{Lip}}.$$

Applying the Gaussian isoperimetric inequality of Borell, Sudakov and Tsirel'son ([7], [28]) to $F = f(I_1(e_1),\dots,I_1(e_n))$ with $\|DF\|_{L^\infty(\Omega,L^2(\mathbb{R}_+))} \le 1$, leads to concentration inequalities. By density of the cylindrical functionals this result extends to Wiener functionals F in the domain of D and satisfying the condition $\|DF\|_{L^\infty(\Omega,L^2(\mathbb{R}_+))} \le 1$. In a similar way, the Gaussian concentration inequalities obtained in [22], [18] or [4], extend to infinite dimensions.

3 Concentration inequalities in the general case

In this section we work in the general framework of normal martingales with the chaos representation property, to do so we extend some arguments of [13].

Lemma 3.1 *Let $F \in \mathrm{Dom}(D)$ be such that $E[e^{t_0|F|}] < \infty$, and $e^{sF} \in \mathrm{Dom}(D)$, $0 < s \le t_0$, for some $t_0 > 0$. Then*

$$E[e^{t(F-E[F])}] \le \exp\left(\int_0^t h(s)ds\right), \quad 0 \le t \le t_0, \tag{3.1}$$

where h is defined as

$$h(s) = \int_0^\infty \|D_u F\|_\infty \|e^{-sF} D_u e^{sF}\|_\infty du, \quad s \in [0, t_0]. \tag{3.2}$$

Proof. Let us first assume that $E[F] = 0$. We have

$$\begin{aligned} E[Fe^{sF}] &= E\left[\int_0^\infty E[D_u F \mid \mathcal{F}_u] E[D_u e^{sF} \mid \mathcal{F}_u] du\right] \\ &= E\left[\int_0^\infty D_u e^{sF} E[D_u F \mid \mathcal{F}_u] du\right] \\ &\leq E[e^{sF}] \int_0^\infty \|D_u F\|_\infty \|e^{-sF} D_u e^{sF}\|_\infty du, \quad 0 \leq s \leq t_0. \end{aligned}$$

In the general case, letting $L(s) = E[e^{s(F-E[F])}]$, we have

$$\log(E[e^{t(F-E[F])}]) = \int_0^t \frac{L'(s)}{L(s)} ds \leq \int_0^t \frac{E[(F-E[F])e^{s(F-E[F])}]}{E[e^{s(F-E[F])}]} ds,$$

$0 \leq t \leq t_0$. □

Given $F \in L^2(\Omega)$ we denote by η_F the process

$$\eta_F(t) = E[D_t F \mid \mathcal{F}_t], \quad t \in \mathbb{R}_+,$$

i.e. we have

$$F = E[F] + \int_0^\infty \eta_F(t) dM_t.$$

A modification of the above proof as

$$\begin{aligned} E[Fe^{sF}] &= E\left[\int_0^\infty D_u e^{sF} \eta_F(u) du\right] \leq E\left[e^{sF} \|e^{-sF} De^{sF}\|_{L^2(\mathbb{R}_+)} \|\eta_F\|_{L^2(\mathbb{R}_+)}\right] \\ &\leq E\left[e^{sF}\right] \|e^{-sF} De^{sF}\|_{L^\infty(\Omega, L^2(\mathbb{R}_+))} \|\eta_F\|_{L^\infty(\Omega, L^2(\mathbb{R}_+))}, \end{aligned}$$

also shows that (3.1) holds with

$$h(s) = \|\eta_F\|_{L^\infty(\Omega, L^2(\mathbb{R}_+))} \|e^{-sF} De^{sF}\|_{L^\infty(\Omega, L^2(\mathbb{R}_+))}.$$

Various deviation inequalities can be obtained from this function, however it will not be used any further since it does not directly involve the norm of DF.

In the next lemma we apply the semi-group correlation identity (2.4). We refer to [19] for other applications of semi-groups, in particular to logarithmic Sobolev inequalities.

Lemma 3.2 *Let $(P_t)_{t \in \mathbb{R}_+}$ satisfy* (2.11). *Let $F \in \mathrm{Dom}(D)$ be such that $E[e^{t_0|F|}] < \infty$, and $e^{sF} \in \mathrm{Dom}(D)$, $0 < s \leq t_0$, for some $t_0 > 0$. Then*

$$E[e^{t(F-E[F])}] \leq \exp\left(\int_0^t h(s) ds\right), \quad 0 \leq t \leq t_0, \tag{3.3}$$

where h is any of the functions

$$h(s) = \|DF\|_{L^\infty(\Omega,L^2(\mathbb{R}_+))}\|e^{-sF}De^{sF}\|_{L^\infty(\Omega,L^2(\mathbb{R}_+))}, \quad s \in [0,t_0], \tag{3.4}$$

$$h(s) = \left\|\frac{e^{-sF}De^{sF}}{DF}\right\|_\infty \|DF\|^2_{L^\infty(\Omega,L^2(\mathbb{R}_+))}, \quad s \in [0,t_0]. \tag{3.5}$$

Proof. Again assume first that $E[F] = 0$. If the Ornstein-Uhlenbeck semi-group satisfies (2.11), then

$$\begin{aligned}
E[Fe^{sF}] &= E\left[\int_0^\infty e^{-v}\int_0^\infty D_u e^{sF} P_v D_u F du dv\right] \\
&\leq E\left[e^{sF}\|e^{-sF}De^{sF}\|_{L^2(\mathbb{R}_+)}\int_0^\infty e^{-v}\|P_v DF\|_{L^2(\mathbb{R}_+)}dv\right] \\
&\leq E\left[e^{sF}\right]\|e^{-sF}De^{sF}\|_{L^\infty(\Omega,L^2(\mathbb{R}_+))}\left\|\int_0^\infty e^{-v}P_v\|DF\|_{L^2(\mathbb{R}_+)}dv\right\|_\infty \\
&\leq E\left[e^{sF}\right]\|e^{-sF}De^{sF}\|_{L^\infty(\Omega,L^2(\mathbb{R}_+))}\int_0^\infty e^{-v}\|DF\|_{L^\infty(\Omega,L^2(\mathbb{R}_+))}dv \\
&\leq E\left[e^{sF}\right]\|e^{-sF}De^{sF}\|_{L^\infty(\Omega,L^2(\mathbb{R}_+))}\|DF\|_{L^\infty(\Omega,L^2(\mathbb{R}_+))}.
\end{aligned}$$

A similar argument shows that

$$\begin{aligned}
E[Fe^{sF}] &= E\left[\int_0^\infty e^{-v}\int_0^\infty D_u e^{sF} P_v D_u F du dv\right] \\
&\leq E\left[e^{sF}\left\|\frac{e^{-sF}De^{sF}}{DF}\right\|_\infty\int_0^\infty e^{-v}\|DFP_vDF\|_{L^1(\mathbb{R}_+)}dv\right] \\
&\leq E\left[e^{sF}\left\|\frac{e^{-sF}De^{sF}}{DF}\right\|_\infty\int_0^\infty e^{-v}\|DF\|_{L^2(\mathbb{R}_+)}\|P_vDF\|_{L^2(\mathbb{R}_+)}dv\right] \\
&\leq E\left[e^{sF}\right]\left\|\frac{e^{-sF}De^{sF}}{DF}\right\|_\infty\|DF\|_{L^\infty(\Omega,L^2(\mathbb{R}_+))}\left\|\int_0^\infty e^{-v}P_v\|DF\|_{L^2(\mathbb{R}_+)}dv\right\|_\infty \\
&\leq E\left[e^{sF}\right]\left\|\frac{e^{-sF}De^{sF}}{DF}\right\|_\infty\|DF\|_{L^\infty(\Omega,L^2(\mathbb{R}_+))}\int_0^\infty e^{-v}\|DF\|_{L^\infty(\Omega,L^2(\mathbb{R}_+))}dv \\
&\leq E\left[e^{sF}\right]\left\|\frac{e^{-sF}De^{sF}}{DF}\right\|_\infty\|DF\|^2_{L^\infty(\Omega,L^2(\mathbb{R}_+))}.
\end{aligned}$$

The remainder of the proof is as in Lemma 3.1. $\square$

From these lemmas a general concentration inequality follows:

Proposition 3.3 *Let $F \in \mathrm{Dom}(D)$ be such that $E[e^{t_0|F|}] < \infty$, and $e^{sF} \in \mathrm{Dom}(D)$, $0 < s \leq t_0$, for some $t_0 > 0$. Let h be the function defined either in* (3.2)*, or (if*

$(\phi_t)_{t\in\mathbb{R}_+}$ *is deterministic) in* (3.4) *or in* (3.5)*. Then*

$$P(F - E[F] \geq x) \leq \exp\left(-\int_0^x h^{-1}(s)ds\right), \quad 0 < x < h(t_0),$$

where h^{-1} is the inverse of h.

Proof. From Lemma 3.1 we have for all $x \in \mathbb{R}_+$:

$$e^{tx} P(F - E[F] \geq x) \leq E[e^{t(F-E[F])}] \leq e^{H(t)}, \quad 0 \leq t \leq t_0,$$

with

$$H(t) = \int_0^t h(s)ds, \quad 0 \leq t \leq t_0.$$

For any $0 < t < t_0$ we have $\frac{d}{dt}(H(t) - tx) = h(t) - x$, hence

$$\begin{aligned} \min_{0<t<t_0} (H(t) - tx) &= H(h^{-1}(x)) - xh^{-1}(x) = \int_0^{h^{-1}(x)} h(s)ds - xh^{-1}(x) \\ &= \int_0^x s dh^{-1}(s) - xh^{-1}(x) = -\int_0^x h^{-1}(s)ds. \end{aligned}$$

□

4 Concentration and deviation inequalities for deterministic structure

In this section we work with $(\phi_t)_{t\in\mathbb{R}_+}$ a deterministic function, i.e. $(M_t)_{t\in\mathbb{R}_+}$ is written as in (2.7). This covers the Gaussian case for $\phi = 0$, and also the general Poisson case, as shown in Sect. 5.

Proposition 4.1 *Let $F \in \mathrm{Dom}(D)$ be such that $E[e^{t_0|F|}] < \infty$, for some $t_0 > 0$. Then*

$$P(F - E[F] \geq x) \leq \exp\left(-\int_0^x h^{-1}(s)ds\right), \quad 0 < x < h(t_0),$$

where h^{-1} is the inverse of any of the following functions:

$$h(t) = \int_0^\infty \frac{j_u}{|\phi_u|} \|D_u F\|_\infty (e^{t|\phi_u|\|D_u F\|_\infty} - 1)du + t\int_0^\infty i_u \|D_u F\|_\infty^2 du, \tag{4.1}$$

$$h(t) = \|DF\|_{L^\infty(\Omega, L^2(\mathbb{R}_+))} \|\phi^{-1}(e^{t|\phi DF|} - 1)\|_{L^\infty(\Omega, L^2(\mathbb{R}_+))}, \tag{4.2}$$

$$h(t) = \left\| \frac{1}{\phi DF}(e^{t\phi DF} - 1) \right\|_\infty \|D_u F\|^2_{L^\infty(\Omega, L^2(\mathbb{R}_+))}, \quad t \in [0, t_0]. \tag{4.3}$$

Proof. In the deterministic case, $e^{-tF}De^{tF} \in L^2(\Omega \times \mathbb{R}_+)$, with

$$e^{-tF}D_u e^{tF} = \frac{j_u}{\phi_u}\left(e^{t\phi_u D_u F} - 1\right) + i_u t D_u F, \quad u \in \mathbb{R}_+, \tag{4.4}$$

which can also be written as

$$e^{-tF}D_u e^{tF} = \frac{1}{\phi_u}\left(e^{t\phi_u D_u F} - 1\right), \tag{4.5}$$

by replacing $\phi_u^{-1}\left(e^{t\phi_u D_u F} - 1\right)$ with its limit as $\phi_u \to 0$, i.e. tD_uF, if $\phi_u = 0$. It remains to apply Proposition 3.3. $\square$

Note that the inequalities given by (4.1), (4.2) and (4.3) are not comparable. Using the bound

$$|\phi_u^{-1}(e^{t\phi_u D_u F} - 1)| \le t|D_u F| e^{t|\phi_u D_u F|},$$

for all values of $\phi_u \in \mathbb{R}$, Proposition 4.1 also holds for the functions

$$h(t) = t\int_0^\infty \|D_u F\|_\infty^2 \|e^{t|\phi_u D_u F|}\|_\infty du,$$

and

$$h(t) = t\|DF\|_{L^\infty(\Omega, L^2(\mathbb{R}_+))} \|e^{t|\phi DF|} DF\|_{L^\infty(\Omega, L^2(\mathbb{R}_+))}, \quad t \in [0, t_0].$$

We will show in the rest of the paper many instances where we can estimate h and h^{-1}.

Proposition 4.2 *Let $F \in \mathrm{Dom}(D)$ be such that $E[e^{t_0|F|}] < \infty$, for some $t_0 > 0$, and $\phi_u D_u F \le K(u)$ a.s., $u \in \mathbb{R}_+$, for some function $K : \mathbb{R}_+ \to \mathbb{R}$. Then*

$$P(F - E[F] \ge x) \le \exp\left(-\int_0^x h^{-1}(s)ds\right), \quad 0 < x < h(t_0),$$

where h^{-1} is the inverse of

$$h(t) = \left\|\frac{1}{K(\cdot)}(e^{tK(\cdot)} - 1)\right\|_\infty \|DF\|^2_{L^\infty(\Omega, L^2(\mathbb{R}_+))}, \quad t \in [0, t_0].$$

Proof. Since the function $x \mapsto (e^x - 1)/x$ is positive and increasing on $\mathbb{R}$, we have

$$0 \le \frac{e^{-tF}D_u e^{tF}}{D_u F} = \frac{1}{\phi_u D_u F}\left(e^{t\phi_u D_u F} - 1\right) \le \frac{1}{K(u)}(e^{tK(u)} - 1), \quad u \in \mathbb{R}_+,$$

and

$$\left|\frac{e^{-tF}D_u e^{tF}}{D_u F}\right| \le \frac{1}{K(u)}(e^{tK(u)} - 1), \quad u \in \mathbb{R}_+.$$

It remains to apply Proposition 3.3 and Lemma 3.2. $\square$

The following corollary is the main result of this section. It unifies the Poisson and Brownian case, and allows in particular to recover the classical inequality (4.7) in the case $\phi = 0$, i.e. on Wiener space cf. [22], and Proposition 3.1 of [30] which is proved from the sharp logarithmic Sobolev inequalities on Poisson space [6].

Corollary 4.3 *Let $F \in \mathrm{Dom}(D)$ be such that $\phi DF \le K$ a.s. for some $K \ge 0$ and $\|DF\|_{L^\infty(\Omega, L^2(\mathbb{R}_+))} < \infty$. Then for $x \ge 0$,*

$$\begin{aligned} P(F - E[F] \ge x) &\le \exp\left(-\frac{\|DF\|^2_{L^\infty(\Omega,L^2(\mathbb{R}_+))}}{K^2} g\left(\frac{xK}{\|DF\|^2_{L^\infty(\Omega,L^2(\mathbb{R}_+))}}\right)\right) \\ &\le \exp\left(-\frac{x}{2K}\log\left(1 + \frac{xK}{\|DF\|^2_{L^\infty(\Omega,L^2(\mathbb{R}_+))}}\right)\right), \end{aligned} \tag{4.6}$$

with $g(u) = (1+u)\log(1+u) - u$, $u \ge 0$. If $K = 0$ (decreasing functionals) we have

$$P(F - E[F] \ge x) \le \exp\left(-\frac{x^2}{2\|DF\|^2_{L^\infty(\Omega,L^2(\mathbb{R}_+))}}\right). \tag{4.7}$$

Proof. We first assume that $F \in \mathrm{Dom}(D)$ is a bounded random variable. The function h defined in Proposition 4.2 satisfies

$$h(t) \le \frac{1}{K}(e^{tK} - 1)\|DF\|^2_{L^\infty(\Omega,L^2(\mathbb{R}_+))},$$

hence

$$\begin{aligned} -\int_0^x h^{-1}(t)dt &\le -\frac{1}{K}\int_0^x \log\left(1 + tK\|DF\|^{-2}_{L^\infty(\Omega,L^2(\mathbb{R}_+))}\right)dt \\ &= -\frac{1}{K}\left((x + \frac{1}{K}\|DF\|^2_{L^\infty(\Omega,L^2(\mathbb{R}_+))})\log\left(1 + xK\|DF\|^{-2}_{L^\infty(\Omega,L^2(\mathbb{R}_+))}\right) - x\right), \end{aligned}$$

and (4.6) holds for all $x \ge 0$ since F is bounded. If $K = 0$, the above proof is still valid by replacing all terms by their limits as $K \to 0$. If $F \in \mathrm{Dom}(D)$ is not bounded the conclusion holds for $F_n = \max(-n, \min(F, n)) \in \mathrm{Dom}(D)$, $n \ge 1$, and $(F_n)_{n\in\mathbb{N}}$, $(DF_n)_{n\in\mathbb{N}}$, converge respectively to F and DF in $L^2(\Omega)$, resp. $L^2(\Omega \times \mathbb{R}_+)$, with $\|DF_n\|^2_{L^\infty(\Omega,L^2(\mathbb{R}_+))} \le \|DF\|^2_{L^\infty(\Omega,L^2(\mathbb{R}_+))}$. □

The bounds (4.6) and (4.7) respectively imply $E[e^{\alpha|F|\log_+|F|}] < \infty$, for some $\alpha > 0$ and $E[e^{\alpha F^2}] < \infty$, for all $\alpha < (2\|DF\|^2_{L^\infty(\Omega,L^2(\mathbb{R}_+))})^{-1}$.

In particular, if F is $\mathcal{F}_T$-measurable with $DF \leq K$ for some $K \geq 0$, and if morevoer $\phi_t = \phi \in \mathbb{R}_+$ is constant in $t \in \mathbb{R}_+$, then

$$P(F - E[F] \geq x) \leq \exp\left(-\frac{T}{\phi^2} g\left(\frac{\phi x}{KT}\right)\right) \leq \exp\left(-\frac{x}{2K\phi} \log\left(1 + \frac{\phi x}{KT}\right)\right),$$

since $\|DF\|_{L^\infty(\Omega, L^2(\mathbb{R}_+))} \leq KT$. This improves (as in [30]) the inequality

$$P(F - E[F] \geq x) \leq \exp\left(-\frac{x}{4\phi K} \log\left(1 + \frac{\phi x}{2KT}\right)\right). \tag{4.8}$$

obtained from Proposition 6.1 in [2] which relies on modified (and not sharp) logarithmic Sobolev inequalities on Poisson space.

Corollary 4.4 *Let $\phi_t = \phi \in \mathbb{R}_+$, $t \in \mathbb{R}_+$, be constant. Let $F \in \mathrm{Dom}(D)$ be such that $\|DF\|_\infty \leq K$ and $\|DF\|_{L^1(\mathbb{R}_+, L^\infty(\Omega))} < \infty$. Then*

$$\begin{aligned} P(F - E[F] \geq x) &\leq \exp\left(-\frac{\|DF\|_{L^1(\mathbb{R}_+, L^\infty(\Omega))}}{\phi^2 K} g\left(\frac{x\phi}{\|DF\|_{L^1(\mathbb{R}_+, L^\infty(\Omega))}}\right)\right) \\ &\leq \exp\left(-\frac{x}{2\phi K} \log\left(1 + \frac{x\phi}{\|DF\|_{L^1(\mathbb{R}_+, L^\infty(\Omega))}}\right)\right), \end{aligned}$$

with $g(u) = (1+u)\log(1+u) - u$, $u \geq 0$, and we have $E[e^{\lambda|F|\log_+|F|}] < \infty$ for some $\lambda > 0$. If $\phi_t = 0$, $t \in \mathbb{R}_+$, and $F \in \mathrm{Dom}(D)$ is such that $\|DF\|^2_L(\mathbb{R}_+, L^\infty(\Omega)) < \infty$, then

$$P(F - E[F] \geq x) \leq \exp\left(-\frac{x^2}{2\|DF\|_{L^2(\mathbb{R}_+, L^\infty(\Omega))}}\right). \tag{4.9}$$

Proof. The function defined in (4.1) of Proposition 4.1 satisfies

$$h(t) \leq \phi^{-1}(e^{t\phi K} - 1)\|DF\|_{L^1(\mathbb{R}_+, L^\infty(\Omega))},$$

which allows to follow the proof of Corollary 4.3. In the limiting case $\phi = 0$, Relation (4.1) gives $h(t) = t\|DF\|_{L^2(\mathbb{R}_+, L^\infty(\Omega))}$, hence $-h^{-1}(t) = -t\|DF\|^{-2}_{L^2(\mathbb{R}_+, L^\infty(\Omega))}$. Again we may first obtain (4.9) when F is bounded and treat the general case via an approximation argument. $\square$

Corollary 4.4 is weaker than Corollary 4.3, however it relies only on the Clark formula (i.e. on (4.1) and Lemma 3.1), not on the use of semi-groups. For this reason it can be stated for any derivation operator D which can be used in the Clark formula. In particular it transfers immediately to the Poisson space for the operator $\tilde{D}$, see Sect. 6.

5 Difference operator on Poisson space

Let X be a σ-compact metric space and let Ω^X denote the set of Radon measures

$$\Omega^X = \left\{ \omega = \sum_{i=1}^{i=N} \epsilon_{t_i} \ : \ (t_i)_{i=1}^{i=N} \subset X, \ t_i \neq t_j, \ \forall i \neq j, \ N \in \mathbb{N} \cup \{\infty\} \right\},$$

where ϵ_t denotes the Dirac measure at $t \in X$. Given $A \in \mathcal{B}(X)$, let $\mathcal{F}_A = \sigma(\omega(B) \ : \ B \in \mathcal{B}(X), \ B \subset A)$. Let σ be a diffuse Radon measure on X, let P denote the Poisson measure with intensity σ on Ω^X and let also $L^2_\sigma(X) = L^2(X, \sigma)$. The multiple Poisson stochastic integral $I_n(f_n)$ is then defined as

$$I_n(f_n)(\omega) = \int_{\Delta_n} f_n(t_1, \dots, t_n)(\omega(dt_1) - \sigma(dt_1)) \cdots (\omega(dt_n) - \sigma(dt_n)), \quad f_n \in L^2_\sigma(X)^{\circ n},$$

with $\Delta_n = \{(t_1, \dots, t_n) \in X^n \ : \ t_i \neq t_j, \ \forall i \neq j\}$, and the isometry formula

$$E[I_n(f_n) I_m(g_m)] = n! \mathbf{1}_{\{n=m\}} \langle f_n, g_m \rangle_{L^2_\sigma(X)^{\circ n}},$$

holds true (see [21]). Moreover every square-integrable random variable $F \in L^2(\Omega^X, P)$ admits the Wiener-Poisson decomposition

$$F = \sum_{n=0}^{\infty} I_n(f_n),$$

in series of multiple stochastic integrals. The linear closable operator

$$D : L^2(\Omega^X, P) \to L^2(\Omega^X \times X, P \otimes \sigma)$$

is defined via

$$D_t I_n(f_n)(\omega) = n I_{n-1}(f_n(*, t))(\omega), \quad P(d\omega) \otimes \sigma(dt) - a.e., \quad n \in \mathbb{N}.$$

It is known, cf. [15] or Proposition 1 of [21], that

$$D_t F(\omega) = F(\omega \cup \{t\}) - F(\omega), \qquad dP \times dt - a.e., \quad F \in \mathrm{Dom}(D),$$

where as a convention we identify $\omega \in \Omega^X$ with its support. Since there exists a measurable map $\tau : X \to \mathbb{R}_+$, a.e. bijective, such that the Lebesgue measure is the image of σ by τ (see e.g. [9], p. 192), Corollary 4.3 and Corollary 4.4 can be restated. Again we recover Proposition 3.1 of [30] in the setting of Poisson random measures on a metric space, without using (sharp) logarithmic Sobolev inequalities:

Corollary 5.1 *Let $F \in \mathrm{Dom}(D)$ be such that $DF \le K$, a.s., for some $K \ge 0$, and $\|DF\|_{L^\infty(\Omega,L^2(X))} < \infty$. Then*

$$\begin{aligned} P(F - E[F] \ge x) &\le \exp\left(-\frac{\|DF\|^2_{L^\infty(\Omega,L^2(X))}}{K^2} g\left(\frac{xK}{\|DF\|^2_{L^\infty(\Omega,L^2(X))}}\right)\right) \\ &\le \exp\left(-\frac{x}{2K}\log\left(1+\frac{xK}{\|DF\|^2_{L^\infty(\Omega,L^2(X))}}\right)\right), \end{aligned}$$

with $g(u) = (1+u)\log(1+u) - u$, $u \ge 0$. If $K = 0$ (decreasing functionals) we have

$$P(F - E[F] \ge x) \le \exp\left(-\frac{x^2}{2\|DF\|^2_{L^\infty(\Omega,L^2(X))}}\right). \tag{5.1}$$

In particular if $F = \int_X f(x)\omega(dx)$, then $\|DF\|_{L^\infty(\Omega,L^2(X))} = \|f\|_{L^2(X)}$ and if $f \le K$, a.s., then

$$P\left(\int_X f(x)(\omega(dx) - \sigma(dx)) \ge x\right) \le \exp\left(-\frac{\int_X f^2(x)\sigma(dx)}{K^2} g\left(\frac{xK}{\int_X f^2(x)\sigma(dx)}\right)\right),$$

which covers Proposition 2 of [27]. If $f \le 0$, a.s., then

$$P\left(\int_X f(x)(\omega(dx) - \sigma(dx)) \ge x\right) \le \exp\left(-\frac{x^2}{2\int_X f^2(x)\sigma(dx)}\right).$$

If $F = \int_X f(x)\omega(dx)$, then $\|DF\|_{L^1(X,L^\infty(\Omega))} = \|f\|_{L^1(X)}$, and we obtain

$$P\left(\int_X f(x)(\omega(dx) - \sigma(dx)) \ge x\right) \le \exp\left(-\frac{\int_X |f(x)|\sigma(dx)}{\|f\|_\infty} g\left(\frac{x}{\int_X |f(x)|\sigma(dx)}\right)\right).$$

In case $f \ge 0$ a.s., this can be written as

$$P\left(\int_X f(x)(\omega(dx) - \sigma(dx)) \ge x\right) \le \exp\left(-\frac{E[F]}{\|f\|_\infty} g\left(\frac{x}{E[F]}\right)\right).$$

As an application we consider as in [27] a family $(\Psi_a)_{a\in\mathbb{N}} \subset L^2(X)$ of functions with values in $[0, K]$, with $\sigma(X) < \infty$, and the functional

$$F = \sup_{a\in\mathbb{N}} \int_X \Psi_a(x)\omega(dx).$$

Then

$$0 \le D_x F = \sup_{a\in\mathbb{N}}\left(\int_X \Psi_a(x)\omega(dx) + \Psi_a(x)\right) - \sup_{a\in\mathbb{N}} \int_X \Psi_a(x)\omega(dx),$$

hence

$$0 \leq D_x F \leq \sup_{a\in\mathbb{N}} \Psi_a(x) \leq K,$$

and

$$P(F - E[F] \geq x) \leq \exp\left(-\sigma(X) g\left(\frac{x}{K\sigma(X)}\right)\right).$$

Moreover,

$$\begin{aligned}
E[F] &= \sum_{n=1}^{\infty} \frac{e^{-\sigma(X)}}{n!} \int_{X^n} \sup_{a\in\mathbb{N}} (\Psi_a(x_1) + \cdots + \Psi_a(x_n)) \sigma(dx_1)\cdots\sigma(dx_n) \\
&\geq \sum_{n=1}^{\infty} \frac{e^{-\sigma(X)}}{n!} \int_{X^n} \sup_{a\in\mathbb{N}} \Psi_a(x_1) \sigma(dx_1)\cdots\sigma(dx_n) \\
&\geq \sum_{n=1}^{\infty} \frac{e^{-\sigma(X)}}{n!} \int_{X^n} \|D_{x_1}F\|_\infty \sigma(dx_1)\cdots\sigma(dx_n) \\
&\geq \|DF\|_{L^1(X, L^\infty(\Omega))} \sum_{n=1}^{\infty} \frac{e^{-\sigma(X)}}{n!} (\sigma(X))^{n-1} \\
&\geq \frac{1}{\sigma(X)} \|DF\|_{L^1(X, L^\infty(\Omega))} (1 - e^{-\sigma(X)}).
\end{aligned}$$

Hence

$$\|DF\|_{L^1(X, L^\infty(\Omega))} \leq \frac{\sigma(X)}{1 - e^{-\sigma(X)}} E[F],$$

and

$$P(F - E[F] \geq x) \leq \exp\left(-\frac{\sigma(X)}{K(1 - e^{-\sigma(X)})} E[F] g\left(\frac{x(1 - e^{-\sigma(X)})}{\sigma(X)E[F]}\right)\right).$$

6 Local gradient on Poisson space

In the Poisson case, if $X = \mathbb{R}_+$ and σ is the Lebesgue measure, then a local gradient can be introduced, cf. [8], [10], [23]. Let $(T_k)_{k\geq 1}$ denote the jump times of the canonical Poisson process $(N_t)_{t\in\mathbb{R}_+}$, and let $\tau_k = T_k - T_{k-1}$, $k \geq 1$, denote its interjump times, with $T_0 = 0$. Let $\mathcal{S}$ denote the set of smooth random functionals F of the form

$$F = f(\tau_1, \ldots, \tau_n), \qquad n \geq 1,$$

where f is of class $\mathcal{C}^1$ on $\mathbb{R}^n$ and has compact support. Let $\tilde{D}$ denote the closable gradient defined as

$$\tilde{D}_t F = -\sum_{k=1}^{k=n} \mathbf{1}_{[T_k, T_{k+1}[}(t) \partial_k f(\tau_1, \ldots, \tau_n), \quad t \in \mathbb{R}_+, \quad F \in \mathcal{S}.$$

Then the relation $E[D_t F \mid \mathcal{F}_t] = E[\tilde{D}_t F \mid \mathcal{F}_t]$ holds, $t \in \mathbb{R}_+$, and the Clark formula can be written for $F \in \mathrm{Dom}(\tilde{D})$ as:

$$F = E[F] + \int_0^\infty E[\tilde{D}_t F \mid \mathcal{F}_t] d(N_t - t), \tag{6.1}$$

cf. Theorem 1 of [23].

Corollary 6.1 *Let $F \in \mathrm{Dom}(\tilde{D})$. We have*

$$P(F - E[F] \geq x) \leq \exp\left(-\frac{x^2}{2\|\tilde{D}F\|^2_{L^2(\mathbb{R}_+, L^\infty(\Omega))}} \right), \tag{6.2}$$

and

$$P(F - E[F] \geq x) \leq \exp\left(-\frac{x^2}{4\|\tilde{D}F\|^2_{L^\infty(\Omega, L^2(\mathbb{R}_+))}} \right). \tag{6.3}$$

Proof. For (6.2) we note that the Wiener space proof of Corollary 4.4 is valid on Poisson space since $\tilde{D}$ satisfies the chain rule of derivation and the Clark formula (6.1). Concerning (6.3), we construct the exponential random variables $(\tau_k)_{k\geq 1}$ as half sums of squared independent Gaussian random variables. Let $F = f(\tau_1, \ldots, \tau_n)$, and consider the Wiener functional ΘF given as

$$\Theta F = f\left(\frac{x_1^2 + y_1^2}{2}, \ldots, \frac{x_n^2 + y_n^2}{2} \right),$$

where $x_1, \ldots, x_n$, $y_1, \ldots, y_n$, denote two independent collections of normal random variables that may be constructed as Brownian single stochastic integrals. Using the fact that F and ΘF have same law, and the relation

$$2\Theta |\tilde{D}F|^2_{L^2(\mathbb{R}_+)} = |\hat{D}\Theta F|^2_{L^2(\mathbb{R}_+)}, \tag{6.4}$$

see Lemma 1 of [24], the application on Wiener space of Corollary 4.3 to ΘF yields (6.3). $\square$

The bounds (6.2) and (6.3) imply the exponential integrability $E[e^{\alpha F^2}] < \infty$ for all $\alpha < (2\|\tilde{D}F\|^2_{L^2(\mathbb{R}_+,L^\infty(\Omega))})^{-1}$, resp. $\alpha < (4\|\tilde{D}F\|^2_{L^\infty(\Omega,L^2(\mathbb{R}_+))})^{-1}$. The above results can be obtained from logarithmic Sobolev inequalities, i.e. by application of Corollary 2.5 of [18] to Theorem 0.7 in [1] (or Relation (4.4) in [18] for a formulation in terms of exponential random variables).

7 Discrete settings

The covariance representations (2.3) and (2.4) which lead to the concentration and deviation inequalities of the previous sections have versions in discrete settings. Our purpose is now to explore consequences of such representations. We consider the discrete structure equation

$$Y_k^2 = 1 + \varphi_k Y_k, \quad k \in \mathbb{N}, \tag{7.1}$$

i.e. $(\varphi_k)_{k\in\mathbb{N}}$ is a deterministic sequence of real numbers, and $(Y_k)_{k\geq 1}$ is a sequence of centered independent random variables. Since (7.1) is a second order equation, there is a family $(X_k)_{k\geq 1}$ of independent Bernoulli $\{-1,1\}$-valued random variables such that

$$Y_k = \frac{\varphi_k + X_k\sqrt{\varphi_k^2+4}}{2}, \quad k \geq 1.$$

The family $(X_k)_{k\in\mathbb{N}}$ is constructed as a family of canonical projections on $\Omega = \{-1,1\}^{\mathbb{N}}$, under the measure P determined from the condition (7.1) and the fact that $E[Y_k] = 0$ (which imply that $E[Y_k^2] = 1$), i.e.

$$p_k = P(X_k = 1) = P\left(Y_k = \sqrt{\frac{q_k}{p_k}}\right) = \frac{1}{2} - \frac{\varphi_k}{2\sqrt{\varphi_k^2+4}}, \quad k \in \mathbb{N},$$

and

$$q_k = P(X_k = -1) = P\left(Y_k = -\sqrt{\frac{p_k}{q_k}}\right) = \frac{1}{2} + \frac{\varphi_k}{2\sqrt{\varphi_k^2+4}} \quad k \in \mathbb{N}.$$

Let $J_n(f_n)$ denote the multiple stochastic integral of $f_n \in \ell^2(\mathbb{N})^{\circ n}$ (the space of square-summable symmetric functions on $\mathbb{N}^n$), defined as

$$J_n(f_n) = \sum_{(k_1,\ldots,k_n)\in\Delta_n} f_n(k_1,\ldots,k_n) Y_{k_1}\cdots Y_{k_n},$$

where

$$\Delta_n = \{(k_1, \ldots, k_n) \in \mathbb{N}^n \ : \ k_i \neq k_j, \ 1 \leq i < j \leq n\},$$

with the isometry

$$E[J_n(f_n)J_m(g_m)] = n!\mathbf{1}_{\{n=m\}}\langle \mathbf{1}_{\Delta_n} f_n, g_m\rangle_{\ell^2(\mathbb{N})^{\otimes n}}.$$

We have

$$J_n(f_n) = n! \sum_{k_n=0}^{\infty} \sum_{0\leq k_{n-1}<k_n} \cdots \sum_{0\leq k_1<k_2} f_n(k_1, \ldots, k_n) Y_{k_1} \cdots Y_{k_n}. \tag{7.2}$$

Let $S_n = \sum_{k=0}^{k=n} (X_k + 1)/2$ be the random walk associated to $(X_k)_{k\geq 0}$, cf. also [12], [20]. If $p_k = p$ and $q_k = q$, $k \in \mathbb{N}$, then $J_n(\mathbf{1}_{[0,N]^n})$ is the Krawtchouk polynomial $K_n(S_N; N+1, p)$ of order n, with parameter $(N+1, p)$, cf. [26]. The set $\mathcal{P}$ of polynomials in $X_1, X_2, X_3, \ldots$ is dense in $L^2(\Omega, P)$, hence any $F \in L^2(\Omega, P)$ can be represented as a series of multiple stochastic integrals:

$$F = \sum_{n=0}^{\infty} J_n(f_n), \quad f_k \in \ell^2(\mathbb{N})^{\circ k}, \ k \geq 0, \quad J_0(f_0) = E[F].$$

Definition 7.1 *We densely define the linear gradient operator* $D : L^2(\Omega) \longrightarrow L^2(\Omega \times \mathbb{N})$ *as*

$$D_k J_n(f_n) = n J_{n-1}(f_n(*, k)\mathbf{1}_{\Delta_n}(*, k)), \qquad f_n \in \ell^2(\mathbb{N})^{\circ n}, \quad n \in \mathbb{N}.$$

We have for $(k_1, \ldots, k_n) \in \Delta_n$

$$D_k \left(\prod_{i=1}^{i=n} Y_{k_i} \right) = \mathbf{1}_{\{l\in\{k_1,\ldots,k_n\}\}} \prod_{\substack{i=1 \\ k_i\neq k}}^{i=n} Y_{k_i},$$

hence the probabilistic interpretation of D_k is

$$D_k F(S_\cdot) = \sqrt{p_k q_k} \left(F(S_\cdot + \mathbf{1}_{\{X_k=-1\}} \mathbf{1}_{\{k\leq \cdot\}}) - F(S_\cdot - \mathbf{1}_{\{X_k=1\}} \mathbf{1}_{\{k\leq \cdot\}}) \right).$$

When restricted to cylindrical functionals of the form

$$F = f(X_1, \ldots, X_n),$$

the gradient D is the finite difference operator

$$D_kF = \sqrt{p_kq_k}\left(f(X_1,\ldots,X_{k-1},+1,X_{k+1},\ldots,X_n) - f(X_1,\ldots,X_{k-1},-1,X_{k+1},\ldots,X_n)\right),$$

which (in the symmetric case $p_k = q_k = 1/2$, $k \in \mathbb{N}$), is the operator considered in [4]. The operator D does not satisfy the same product rules as in the continuous time case (Relation (2.8)), instead we have:

Proposition 7.2 *Let $F, G : \Omega \to \mathbb{R}$. Then,*

$$D_k(FG) = FD_kG + GD_kF - \frac{X_k}{\sqrt{p_kq_k}}D_kFD_kG, \quad k \geq 0,$$

and

$$D_ke^F = -X_k\sqrt{p_kq_k}e^F\left(e^{-\frac{X_k}{\sqrt{p_kq_k}}D_kF} - 1\right). \tag{7.3}$$

Proof. Let $F_+^k = F(S_\cdot + \mathbf{1}_{\{X_k=-1\}}\mathbf{1}_{\{k\leq\cdot\}})$ and $F_k^- = F(S_\cdot - \mathbf{1}_{\{X_k=1\}}\mathbf{1}_{\{k\leq\cdot\}})$, $k \geq 0$. We have

$$\begin{aligned}
D_k(FG) &= \sqrt{p_kq_k}(F_k^+G_k^+ - F_k^-G_k^-) \\
&= \mathbf{1}_{\{X_k=-1\}}\sqrt{p_kq_k}\left(F(G_k^+ - G) + G(F_k^+ - F) + (F_k^+ - F)(G_k^+ - G)\right) \\
&\quad +\mathbf{1}_{\{X_k=1\}}\sqrt{p_kq_k}\left(F(G - G_k^-) + G(F - F_k^-) - (F - F_k^-)(G - G_k^-)\right) \\
&= \mathbf{1}_{\{X_k=-1\}}\left(FD_kG + GD_kF + \frac{1}{\sqrt{p_kq_k}}D_kFD_kG\right) \\
&\quad +\mathbf{1}_{\{X_k=1\}}\left(FD_kG + GD_kF - \frac{1}{\sqrt{p_kq_k}}D_kFD_kG\right).
\end{aligned}$$

We have

$$\begin{aligned}
D_ke^F &= \mathbf{1}_{\{X_k=1\}}\sqrt{p_kq_k}(e^F - e^{F_k^-}) + \mathbf{1}_{\{X_k=-1\}}\sqrt{p_kq_k}(e^{F_k^+} - e^F) \\
&= \mathbf{1}_{\{X_k=1\}}\sqrt{p_kq_k}e^F(1 - e^{-\frac{1}{\sqrt{p_kq_k}}D_kF}) + \mathbf{1}_{\{X_k=-1\}}\sqrt{p_kq_k}e^F(e^{\frac{1}{\sqrt{p_kq_k}}D_kF} - 1) \\
&= -X_k\sqrt{p_kq_k}e^F\left(e^{-\frac{X_k}{\sqrt{p_kq_k}}D_kF} - 1\right).
\end{aligned}$$

$\square$

The next result is the predictable representation of the functionals of $(S_n)_{n\geq 0}$. Let $\mathcal{F}_N = \sigma(X_0,\ldots,X_N)$, $N \in \mathbb{N}$.

Proposition 7.3 *We have the Clark formula*

$$F = E[F] + \sum_{k=1}^{\infty} E[D_k F \mid \mathcal{F}_{k-1}] Y_k, \quad F \in L^2(\Omega).$$

Proof. For $F = J_n(f_n)$ we have, using (7.2) (see e.g. [26]):

$$\begin{aligned} F &= J_n(f_n) = n! J_n(f_n \mathbf{1}_{\Delta_n}) = n \sum_{k=1}^{\infty} J_{n-1}(f_n(\cdot, k) \mathbf{1}_{[1,k-1]^{n-1}}(\cdot)) Y_k \\ &= \sum_{k=1}^{\infty} E[D_k J_n(f_n) \mid \mathcal{F}_{k-1}] Y_k. \end{aligned}$$

This identity also shows that $F \mapsto E[D.F \mid \mathcal{F}_{.-1}]$ has norm equal to one as an operator from $L^2(\Omega)$ into $L^2(\Omega \times \mathbb{N})$:

$$\| E[D.F \mid \mathcal{F}_{.-1}] \|^2_{L^2(\Omega \times \mathbb{N})} = \| F - E[F] \|^2_{L^2(\Omega)} \leq \| F - E[F] \|^2_{L^2(\Omega)} + E[F]^2 \leq \| F \|^2_{L^2(\Omega)},$$

hence the Clark formula extends to $F \in L^2(\Omega)$. □

The Clark formula implies the covariance identity

$$\mathrm{Cov}(F, G) = E \left[\sum_{k=1}^{\infty} D_k F E \left[D_k G \mid \mathcal{F}_{k-1} \right] \right], \tag{7.4}$$

and we also have as in the continuous time case:

$$\mathrm{Cov}(F, G) = E \left[\sum_{k=1}^{\infty} \int_0^{\infty} e^{-s} D_k F P_s D_k G ds \right], \tag{7.5}$$

where $(P_t)_{t \in \mathbb{R}_+}$ denotes the semi-group

$$P_t F = \sum_{n=0}^{\infty} e^{-nt} J_n(f_n), \quad t \in \mathbb{R}_+,$$

$F = \sum_{n=0}^{\infty} J_n(f_n)$. The next result shows that the semi-group $(P_t)_{t \in \mathbb{R}_+}$ admits a representation by a probability kernel and an Ornstein-Uhlenbeck type process which (in the symmetric case $p_k = q_k = 1/2$, $k \in \mathbb{N}$) is in fact the Brownian motion on $\{-1, 1\}^N$ considered in [2].

Proposition 7.4 *For $F \in L^2(\Omega, \mathcal{F}_N)$,*

$$P_t F(\omega') = \int_{\Omega} F(\omega) q_t^N(\omega, \omega') dP(\omega), \quad \omega, \omega' \in \Omega, \tag{7.6}$$

where $q_t^N(\omega,\omega')$ is the kernel

$$q_t^N(\omega,\omega') = \prod_{i=1}^{i=N}(1+e^{-t}Y_i(\omega)Y_i(\omega')), \quad \omega,\omega'\in\Omega.$$

Proof. Since $L^2(\Omega,\mathcal{F}_N)$ is finite (2^{N+1}-)dimensional it suffices to consider the functional $Y_{k_1}\cdots Y_{k_n}$ with $(k_1,\ldots,k_n)\in\Delta_n$. We have for $\omega'\in\Omega$, $k\in\mathbb{N}$:

$$\begin{aligned} &E\left[Y_k(\cdot)(1+e^{-t}Y_k(\cdot)Y_k(\omega'))\right] \\ &= p_k\sqrt{\frac{q_k}{p_k}}\left(1+e^{-t}\sqrt{\frac{q_k}{p_k}}Y_k(\omega')\right) - q_k\sqrt{\frac{p_k}{q_k}}\left(1-e^{-t}\sqrt{\frac{p_k}{q_k}}Y_k(\omega')\right) = e^{-t}Y_k(\omega'),\end{aligned}$$

which implies by independence of $(X_k)_{k\in\mathbb{N}}$:

$$P_t(Y_{k_1}\cdots Y_{k_n})(\omega') = e^{-nt}Y_{k_1}(\omega')\cdots Y_{k_n}(\omega') = E[Y_{k_1}\cdots Y_{k_n}q_t^N(\cdot,\omega')], \quad \omega'\in\Omega.$$

□

The Ornstein-Uhlenbeck process $((X_k^t)_{k\in\mathbb{N}})_{t\in\mathbb{R}_+}$ associated to $(P_t)_{t\in\mathbb{R}_+}$ satisfies

$$\begin{aligned} &P(X_k^t=1 \mid X_k^0=1) = p_k+e^{-t}q_k, \qquad P(X_k^t=-1 \mid X_k^0=1) = q_k(1-e^{-t}), \\ &P(X_k^t=1 \mid X_k^0=-1) = p_k(1-e^{-t}) \quad P(X_k^t=-1 \mid X_k^0=-1) = q_k+e^{-t}p_k, \quad k\in\mathbb{N}.\end{aligned}$$

In other terms, the hitting time $\tau_{1,-1}\in\mathbb{R}_+\cup\{+\infty\}$ of -1 starting from $+1$, resp. of $+1$ starting from -1, has distribution

$$P(\tau_{1,-1}<t) = q_k(1-e^{-t}), \quad t\in\mathbb{R}_+,$$

resp.

$$P(\tau_{-1,1}<t) = p_k(1-e^{-t}), \quad t\in\mathbb{R}_+.$$

The covariance identity (7.5) and the representation (7.6) imply the inequality

$$\|P_sDF\|_{L^\infty(\Omega,\ell^2(\mathbb{N}))} \le \|P_s|DF|_{\ell^2(\mathbb{N})}\|_{L^\infty(\Omega)} \le \|DF\|_{L^\infty(\Omega,\ell^2(\mathbb{N}))}, \quad s\in\mathbb{R}_+,$$

for $F\in\mathrm{Dom}(D)$, hence the next proposition can be proved in a way similar to Proposition 3.3.

Proposition 7.5 *Let $F \in \mathrm{Dom}(D)$. Then*

$$E[e^{t(F-E[F])}] \leq \exp\left(\int_0^t h(s)ds\right), \quad 0 \leq t \leq t_0, \tag{7.7}$$

where h is any of the following functions:

$$h(s) = \sum_{k=0}^{\infty} \|D_k F\|_\infty \left\|e^{-sF} D_k e^{sF}\right\|_\infty, \tag{7.8}$$

$$h(s) = \|DF\|_{L^\infty(\Omega,\ell^2(\mathbb{N}))} \left\|e^{-sF} D e^{sF}\right\|_{L^\infty(\Omega,\ell^2(\mathbb{N}))}, \tag{7.9}$$

$$h(s) = \left\|\frac{e^{-sF} D e^{sF}}{DF}\right\|_\infty \|DF\|^2_{L^\infty(\Omega,\ell^2(\mathbb{N}))}, \quad s \in [0, t_0]. \tag{7.10}$$

Although D does not satisfy the same product rule as in the continuous case, from (7.3) we still have the bound

$$|e^{-sF} D_k e^{sF}| \leq \sqrt{p_k q_k}(e^{\frac{s}{\sqrt{p_k q_k}}|D_k F|} - 1), \quad k \in \mathbb{N}, \tag{7.11}$$

which gives the following corollary to Proposition 7.5.

Corollary 7.6 *Let $F \in \mathrm{Dom}(D)$. Then*

$$E[e^{t(F-E[F])}] \leq \exp\left(\int_0^t h(s)ds\right), \quad 0 \leq t \leq t_0, \tag{7.12}$$

where h is any of the following functions:

$$h(s) = \sum_{k=0}^{\infty} \|D_k F\|_\infty \left\|\sqrt{p_k q_k}(e^{\frac{s}{\sqrt{p_k q_k}}|D_k F|} - 1)\right\|_\infty, \tag{7.13}$$

$$h(s) = \|DF\|_{L^\infty(\Omega,\ell^2(\mathbb{N}))} \left\|\sqrt{p_. q_.}(e^{\frac{s}{\sqrt{p_. q_.}}|D_. F|} - 1)\right\|_{L^\infty(\Omega,\ell^2(\mathbb{N}))}, \tag{7.14}$$

$$h(s) = \left\|\sqrt{p_k q_k}\frac{1}{D_k F}(e^{\frac{s}{\sqrt{p_k q_k}}|D_k F|} - 1)\right\|_\infty \|DF\|^2_{L^\infty(\Omega,\ell^2(\mathbb{N}))}, \quad s \in [0, t_0]. \tag{7.15}$$

Again, the inequalities given by (7.13), (7.14) and (7.15) are not comparable. The bound $\sqrt{p_k q_k}(e^{\frac{s}{\sqrt{p_k q_k}}|D_k F|} - 1) \leq s|D_k F| e^{s\frac{1}{\sqrt{p_k q_k}}|D_k F|}$, $k \in \mathbb{N}$, also shows that Corollary 7.6 holds with

$$h(s) = s\sum_{k=0}^{\infty} \|D_k F\|^2_\infty \left\|e^{\frac{s}{\sqrt{p_k q_k}}|D_k F|}\right\|_\infty,$$

and

$$h(s) = s\|DF\|_{L^\infty(\Omega,\ell^2(\mathbb{N}))} \|e^{\frac{s}{\sqrt{p_. q_.}}|D_. F|} D_. F\|_{L^\infty(\Omega,\ell^2(\mathbb{N}))}, \quad s \in [0, t_0].$$

The following corollary is obtained with the same proof as on the Poisson space.

Corollary 7.7 *Let $F \in \mathrm{Dom}(D)$ be such that $\frac{1}{\sqrt{p_k q_k}} |D_k F| \le K$, $k \in \mathbb{N}$, for some $K \ge 0$, and $\|DF\|_{L^\infty(\Omega,\ell^2(\mathbb{N}))} < \infty$. Then*

$$\begin{aligned} P(F - E[F] \ge x) &\le \exp\left(-\frac{\|DF\|^2_{L^\infty(\Omega,\ell^2(\mathbb{N}))}}{K^2} g\left(\frac{xK}{\|DF\|^2_{L^\infty(\Omega,\ell^2(\mathbb{N}))}} \right) \right) \\ &\le \exp\left(-\frac{x}{2K} \log\left(1 + \frac{xK}{\|DF\|^2_{L^\infty(\Omega,\ell^2(\mathbb{N}))}} \right) \right), \end{aligned}$$

with $g(u) = (1+u)\log(1+u) - u$, $u \ge 0$.

Proof. Use the inequality

$$-s \le \frac{e^{-sF} D_k e^{sF}}{D_k F} = -X_k \sqrt{p_k q_k} \frac{1}{D_k F} (e^{-s \frac{X_k}{\sqrt{p_k q_k}} D_k F} - 1) \le \frac{e^{sK} - 1}{K},$$

and apply Corollary 7.6. □

In case $p_k = p$ and $q_k = q$, for all $k \in \mathbb{N}$, the conditions $\frac{1}{\sqrt{pq}} |D_k F| \le \beta$, $k \in \mathbb{N}$, and $\|DF\|^2_{L^\infty(\Omega,\ell^2(\mathbb{N}))} \le \alpha^2$, give

$$P(F - E[F] \ge x) \le \exp\left(-\frac{\alpha^2 pq}{\beta^2} g\left(\frac{x\beta}{\alpha^2 pq} \right) \right) \le \exp\left(-\frac{x}{2\beta} \log\left(1 + \frac{x\beta}{\alpha^2 pq} \right) \right),$$

which is relation (13) obtained on $\{0,1\}^n$ in [6]. In particular if F is $\mathcal{F}_N$-measurable, then

$$P(F - E[F] \ge x) \le \exp\left(-Ng\left(\frac{x}{\beta N} \right) \right) \le \exp\left(-\frac{x}{\beta} \left(\log\left(1 + \frac{x}{\beta N} \right) - 1 \right) \right).$$

Finally we show a Gaussian concentration inequality for functionals of $(S_n)_{n\in\mathbb{N}}$, using the covariance identity (7.4). We refer to [5], [3], [14], [16], for other versions of this inequality.

Proposition 7.8 *Let $F : \Omega \to \mathbb{R}$ be such that*

$$\left\| \sum_{k=0}^{\infty} \frac{1}{2(p_k \wedge q_k)} |D_k F| \|D_k F\|_\infty \right\|_\infty \le K^2.$$

Then

$$P(F - E[F] \ge x) \le \exp\left(-\frac{x^2}{2K^2} \right), \quad x \ge 0.$$

Proof. Using the inequality

$$|e^{tx} - e^{ty}| \le \frac{1}{2}t|x-y|(e^{tx}+e^{ty}), \qquad x, y \in \mathbb{R}, \tag{7.16}$$

we have

$$\begin{aligned}
|D_k e^{tF}| &= \sqrt{p_k q_k}|e^{tF_k^+} - e^{tF_k^-}| \le \frac{1}{2}\sqrt{p_k q_k} t |F_k^+ - F_k^-|(e^{tF_k^+} + e^{tF_k^-}) \\
&= \frac{1}{2}t|D_k F|(e^{tF_k^+} + e^{tF_k^-}) \le \frac{1}{2(p_k \wedge q_k)} t |D_k F| E\left[e^{tF} \mid X_i, \ i \neq k\right] \\
&= \frac{1}{2(p_k \wedge q_k)} t E\left[e^{tF}|D_k F| \mid X_i, \ i \neq k\right],
\end{aligned}$$

and

$$\begin{aligned}
E[Fe^{tF}] &= \sum_{k=0}^{\infty} E[E[D_k F \mid \mathcal{F}_{k-1}] D_k e^{tF}] \le \sum_{k=0}^{\infty} \|D_k F\|_\infty E\left[|D_k e^{tF}|\right] \\
&\le t \sum_{k=0}^{\infty} \frac{1}{2(p_k \wedge q_k)} \|D_k F\|_\infty E\left[E\left[e^{tF}|D_k F| \mid X_i, \ i \neq k\right]\right] \\
&= tE\left[e^{tF} \sum_{k=0}^{\infty} \frac{1}{2(p_k \wedge q_k)} \|D_k F\|_\infty |D_k F|\right] \\
&\le tE[e^{tF}] \left\| \sum_{k=0}^{\infty} \frac{1}{2(p_k \wedge q_k)} |D_k F| \|D_k F\|_\infty \right\|_\infty .
\end{aligned}$$

We can conclude as in the proof of Corollary 4.4. $\square$

In case $p_k = p \le 1/2$ for all $k \in \mathbb{N}$, we obtain

$$P(F - E[F] \ge x) \le \exp\left(-\frac{px^2}{\|DF\|^2_{\ell^2(\mathbb{N}, L^\infty(\Omega))}}\right).$$

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