Convergence rate of $X^N - X$ for McKean equations

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Todo list

1 What is this?

An adaptation of [1, Proposition 3.1] for the case of McKean SDEs proposed in [3].

Hola The proof builds on a number of results presented in the sections below.

2 Some useful definitions and results

Here we present some results and definitions to refer on the text.

Definition 1. *For any real-valued continuous semi-martingale, the local time at zero $L_t^0(\bar{Y})$ is defined as*

$$L_t^0(\bar{Y}) = \lim_{\epsilon \to 0} \frac{1}{2\epsilon} \int_0^t \mathbb{1}_{\{|\bar{Y}| \leq \epsilon\}} d\langle \bar{Y} \rangle_s, \ \mathbb{P}\text{-}a.s. \tag{1}$$

For all $t \geq 0$.

The first result, [1, Lemma 5.1], is not necessary to prove for this particular setting since the result holds for any semi-martingale, I include it here for self-containment reasons.

Lemma 1. *For any $\epsilon \in (0,1)$ and any real-valued, continuous semi-martingale Z we have*

$$\begin{aligned}\mathbb{E}[L_t^0(Z_s)] \leq & 4\epsilon - \mathbb{E}\left[\int_0^t \left(\mathbb{1}_{\{Z_s \in (0,\epsilon)\}} + \mathbb{1}_{\{Z_s \geq \epsilon\}} e^{1-Z_s/\epsilon}\right) dZ_s\right] \\ & + \frac{1}{\epsilon}\mathbb{E}\left[\int_0^t \mathbb{1}_{\{Z>\epsilon} e^{1-Z_s/\epsilon\}} d\langle Z \rangle_s\right].\end{aligned}$$

Let us introduce the original and regularised Kolmogorov equations.

Definition 2. *Kolmogorov equations*
For $\beta \in (0, 1/2)$ let $b \in C_T\mathcal{C}^{-\beta}$, $u, u^N \in C_T\mathcal{C}^{(1+\beta)+}$, and $b^N \to b$ as $N \to \infty$ in $C_T\mathcal{C}^{-\beta}$ The equations

$$\begin{cases} \partial u_i + \frac{1}{2} b_i \Delta u_i = \lambda u_i - b_i \\ u_i(T) = 0, \end{cases} \tag{2}$$

$$\begin{cases} \partial u_i^N + \frac{1}{2} b_i^N \Delta u_i^N = \lambda u_i^N - b_i^N \\ u_i^N(T) = 0. \end{cases} \tag{3}$$

are called Kolmogorov and regularised Kolmogorov equations. Here written component wise.

Lemma 2. *Let*

type this result which is lemma 4.2 in the paper

3 Bounds for the difference of solutions to the Kolmogorov equations

We need a bound for $u - u^N$ and $\nabla u - \nabla u^N$ in L_∞ for the case in which $u \in C_T\mathcal{C}^{1+\alpha}$ for some $\alpha > \beta$ which is an adaptation of [1, Lemma 5.2].

The result builds on top of the following result:

Proposition 1 (Bound for the ρ-equivalent norm of $u - u^N$)**.** *Let u, u^N be (mild) solutions to the Kolmogorov equations from Definition 2 then as $N \to \infty$*

$$\|u_i - u_i^N\|_{C_T\mathcal{C}^{1+\alpha}}^{(\rho)} \leq \frac{cT^{\frac{1-\beta-\alpha}{2}} \|b_i - b_i^N\|_{C_T\mathcal{C}^{-\beta}} (\|u_i\|_{C_T\mathcal{C}^{1+\alpha}} - 1)}{1 - c\rho^{\frac{\alpha+\beta-1}{2}} (\|b\|_{C_T\mathcal{C}^{-\beta}} + \lambda)} \tag{4}$$

for $\rho \geq \rho_0$, where

$$\rho_0 = 2c(\|b_i\|_{C_T\infty+\alpha} + \lambda)^{\frac{2}{\alpha+\beta+1}} \tag{5}$$

and $\lambda > 0$.

Proof. See that $u^N(T) = u(T) = 0$, and in [2], set g^N, g as b^N, b respectively. See that $b^N \to b$. Then let us reformulate the rest of the aforementioned result for $\lambda \neq 0$.

As u^N, u are mild solutions, we have

$$\begin{aligned} u_i(t) - u_i^N(t) &= P_{T-t}(u_i(T) - u_i^N(T)) \\ &\quad + \int_t^T P_{s-t}(\nabla u_i b_i - \nabla u_i^N b_i^N) ds \\ &\quad - \int_t^T P_{s-t}(\lambda u_i + b_i - \lambda u_i^N + b_i^N) ds \\ &= \int_t^T P_{s-t}(\nabla u_i b_i - \nabla u_i^N b_i^N) ds \end{aligned}$$

$$
\begin{aligned}
&- \lambda \int_t^T P_{s-t}(u_i - u_i^N)ds \\
&- \int_t^T P_{s-t}(b_i - b_i^N)ds \\
&= \int_t^T P_{s-t}[(\nabla u_i b_i - \nabla u_i b_i^N) + (\nabla u_i b_i^N - \nabla u_i^N b_i^N)]ds \\
&- \lambda \int_t^T P_{s-t}(u_i - u_i^N)ds \\
&- \int_t^T P_{s-t}(b_i - b_i^N)ds \\
&= \int_t^T P_{s-t}(\nabla u_i b_i - \nabla u_i b_i^N)ds \\
&+ \int_t^T P_{s-t}(\nabla u_i b_i^N - \nabla u_i^N b_i^N)ds \\
&- \lambda \int_t^T P_{s-t}(u_i - u_i^N)ds \\
&- \int_t^T P_{s-t}(b_i - b_i^N)ds
\end{aligned}
$$

Now let us compute the ρ-equivalent norm of $u - u^N$, for some $\alpha > \beta$

this norm is wrong, should be $1 + \alpha$ on the lhs and everywhere else

$$
\begin{aligned}
\|u_i - u_i^N\|_{C_T \mathcal{C}^{-\beta}}^{(\rho)} &= \sup_{0 \le t \le T} e^{-\rho(T-t)} \|u(t) - u^N(t)\|_{1+\alpha} \\
&\le \sup_{0 \le t \le T} e^{-\rho(T-t)} \| \int_t^T P_{s-t}(\nabla u_i b_i - \nabla u_i b_i^N)ds\|_{1+\alpha} \\
&+ \sup_{0 \le t \le T} e^{-\rho(T-t)} \| \int_t^T P_{s-t}(\nabla u_i b_i^N - \nabla u_i^N b_i^N)ds\|_{1+\alpha} \\
&- \sup_{0 \le t \le T} e^{-\rho(T-t)} \|\lambda \int_t^T P_{s-t}(u_i - u_i^N)ds\|_{1+\alpha} \\
&- \sup_{0 \le t \le T} e^{-\rho(T-t)} \| \int_t^T P_{s-t}(b_i - b_i^N)ds\|_{1+\alpha}.
\end{aligned}
$$

Let us take each term from the right hand side of the inequality and bound them.

For the first term, using $\gamma + 2\theta = 1 + \alpha$, $\gamma = -\beta$, $\theta = \frac{1+\alpha+\beta}{2}$, $\|P_t f\|_{\gamma+2\theta} \le ct^{-\theta}\|f\|_\gamma\|$ and $\|\nabla g\|_\xi \le c\|g\|_{\xi+1}$

$$
\begin{aligned}
&\sup_{0 \le t \le T} e^{-\rho(T-t)} \left\| \int_t^T P_{s-t}(\nabla u_i b_i - \nabla u_i b_i^N)ds \right\|_{1+\alpha} \\
&\qquad \le \sup_{0 \le t \le T} e^{-\rho(T-t)} \int_t^T (s-t)^{-\theta} \|\nabla u_i\|_\alpha \|b_i - b_i^N\|_{-\beta}
\end{aligned}
$$

$$\leq c\|u_i\|_{C_T\mathcal{C}_{1+\alpha}}\|b_i - b_i^N\|_{C_T\mathcal{C}^{-\beta}} \sup_{0\leq t\leq T} e^{-\rho(T-t)}(T-t)^{\frac{1-\beta-\alpha}{2}}$$
$$\leq cT^{\frac{1-\beta-\alpha}{2}}\|u_i\|_{C_T\mathcal{C}_{1+\alpha}}\|b_i - b_i^N\|_{C_T\mathcal{C}^{-\beta}}$$

For the second term, see that for $N \to \infty$, we have $\|b^N\|_{C_T\mathcal{C}^{-\beta}} \leq 2\|b\|_{C_T\mathcal{C}^{-\beta}}$

$$\sup_{0\leq t\leq T} e^{-\rho(T-t)}\left\|\int_t^T P_{s-t}b_i^N(\nabla u_i - \nabla u_i^N)ds\right\|_{1+\alpha}$$
$$\leq c\sup_{0\leq t\leq T}\int_t^T (s-t)^{-\theta}e^{-\rho(T-t)}2\|b_i\|_{-\beta}\|\nabla u_i - \nabla u_i^N\|_\alpha ds$$
$$\leq c\|b_i\|_{C_T\mathcal{C}^{-\beta}}\|u_i - u_i^N\|^{(\rho)}_{C_T\mathcal{C}^{-\beta}}\int_t^T (s-t)^{-\theta}e^{-\rho(T-t)}ds$$
$$\leq c\|b_i\|_{C_T\mathcal{C}^{-\beta}}\|u_i - u_i^N\|^{(\rho)}_{C_T\mathcal{C}^{-\beta}}\rho^{\frac{\alpha+\beta-1}{2}}$$

For the third term, which is the one that difers from the proof in [2] we need to use that $\|P_tf\|_{\gamma+2\theta} \leq ct^{-\theta}\|f\|_\gamma$, and in this case we have $\gamma + 2\theta = 1+\alpha$ and $\gamma = 1+\alpha$, so that $\theta = 0$ because $u, u^N \in C_T\mathcal{C}^{1+\alpha}$, so we will have

$$\sup_{0\leq t\leq T} e^{-\rho(T-t)}\left\|\lambda\int_t^T P_{s-t}(u_i - u_i^N)ds\right\|_{1+\alpha}$$
$$\leq c\lambda\sup_{0\leq t\leq T} e^{-\rho(T-t)}\int_t^T (s-t)^{-0}\|u_i - u_i^N\|_{1+\alpha}ds$$
$$= c\lambda\sup_{0\leq t\leq T} e^{-\rho(T-t)}\int_t^T e^{-\rho(T-s)}\sup_{0\leq s\leq T} e^{-\rho(T-s)}\|u_i - u_i^N\|_{1+\alpha}ds$$
$$= c\lambda\sup_{0\leq t\leq T}\|u_i - u_i^N\|^{(\rho)}_{C_T\mathcal{C}_{1+\alpha}}\int_t^T e^{-\rho(T-s)}e^{-\rho(T-t)}ds$$
$$= c\lambda\sup_{0\leq t\leq T}\|u_i - u_i^N\|^{(\rho)}_{C_T\mathcal{C}_{1+\alpha}}\int_t^T e^{-\rho(s-t)}ds$$
$$= c\lambda\sup_{0\leq t\leq T}\|u_i - u_i^N\|^{(\rho)}_{C_T\mathcal{C}_{1+\alpha}}\sup_{0\leq t\leq T}\rho^{-1}[1 - e^{-\rho(T-t)}]$$
$$\leq c\lambda\sup_{0\leq t\leq T}\|u_i - u_i^N\|^{(\rho)}_{C_T\mathcal{C}_{1+\alpha}}\rho^{-1}$$
$$\leq c\lambda\sup_{0\leq t\leq T}\|u_i - u_i^N\|^{(\rho)}_{C_T\mathcal{C}_{1+\alpha}}\rho^{\frac{\alpha+\beta-1}{2}}$$

And for the last term

$$\sup_{0\leq t\leq T} e^{-\rho(T-t)}\left\|\int_t^T P_{T-s}(b_i - b_i^N)ds\right\|_{1+\alpha}$$
$$\leq c\sup_{0\leq t\leq T} e^{-\rho(T-t)}\int_t^T (s-t)^{-\frac{\alpha+\beta-1}{2}}\|b_i - b_i^N\|_{-\beta}ds$$

$$\leq c\|b_i - b_i^N\|_{C_T\mathcal{C}^{-\beta}} \sup_{0\leq t\leq T} e^{-\rho(T-t)}(s-t)^{-\frac{\alpha+\beta-1}{2}}$$
$$\leq cT^{\frac{1-\beta-\alpha}{2}}\|b_i - b_i^N\|_{C^T\mathcal{C}^{-\beta}}$$

Putting everything together

$$\begin{aligned}\|u_i - u_i^N\|^{(\rho)}_{C_T\mathcal{C}^{-\beta}} \leq\ & cT^{\frac{1-\beta-\alpha}{2}}\|u_i\|_{C_T\mathcal{C}^{1+\alpha}}\|b_i - b_i^N\|_{C_T\mathcal{C}^{-\beta}} \\ & + c\|b_i\|_{C_T\mathcal{C}^{-\beta}}\|u_i - u_i^N\|^{(\rho)}_{C_T\mathcal{C}^{-\beta}}\rho^{\frac{\alpha+\beta-1}{2}} \\ & - c\lambda \sup_{0\leq t\leq T}\|u_i - u_i^N\|^{(\rho)}_{C_T\mathcal{C}_{1+\alpha}}\rho^{\frac{\alpha+\beta-1}{2}} \\ & - cT^{\frac{1-\beta-\alpha}{2}}\|b_i - b_i^N\|_{C^T\mathcal{C}^{-\beta}},\end{aligned}$$

and finally,

$$\begin{aligned}\|u_i - u_i^N\|^{(\rho)}_{C_T\mathcal{C}^{-\beta}}&(1 - c\rho^{\frac{\alpha+\beta-1}{2}}[\|b\|_{C_T\mathcal{C}^{-\beta}} + \lambda]) \\ & \leq cT^{\frac{1-\beta-\alpha}{2}}\|b_i - b_i^N\|_{C^T\mathcal{C}^{-\beta}}(\|u_i\|_{C_T\mathcal{C}^{1+\alpha}} - 1) \\ \|u_i - u_i^N\|^{(\rho)}_{C_T\mathcal{C}^{-\beta}} & \leq \frac{cT^{\frac{1-\beta-\alpha}{2}}\|b_i - b_i^N\|_{C^T\mathcal{C}^{-\beta}}(\|u_i\|_{C_T\mathcal{C}^{1+\alpha}} - 1)}{(1 - c\rho^{\frac{\alpha+\beta-1}{2}}[\|b\|_{C_T\mathcal{C}^{-\beta}} + \lambda])}\end{aligned}$$

As required. □

Note that in the above we can represent the right hand side of the inequality as

$$\|u_i - u_i^N\|^{(\rho)}_{C_T\mathcal{C}^{-\beta}} \leq \frac{cT^{\frac{1-\beta-\alpha}{2}}(\|u_i\|_{C_T\mathcal{C}^{1+\alpha}} - 1)}{(1 - c\rho^{\frac{\alpha+\beta-1}{2}}[\|b\|_{C_T\mathcal{C}^{-\beta}} + \lambda])}\|b_i - b_i^N\|_{C^T\mathcal{C}^{-\beta}} \tag{6}$$

Check this norm

$$\|u_i - u_i^N\|^{(\rho)}_{C_T\mathcal{C}^{-\beta}} \leq c(\rho)\|b_i - b_i^N\|_{C^T\mathcal{C}^{-\beta}} \tag{7}$$

Here is the adaptation of [1, Lemma 5.2].

Proposition 2. *Bounds for $\|u - u^N\|_{L_\infty}$ and $\|\nabla u - \nabla u^N\|_{L_\infty}$*

Let $\beta \in (0, 1/2)$ and $b \in C_T\mathcal{C}^{-\beta}$. Let $u, u^N \in C_T\mathcal{C}^{(1+\beta)+}$ be (mild) solutions to the Kolmogorov equations from Definition 2.

Assume, by Proposition 1, that for some $\alpha > \beta$

$$\|u - u^N\|^{(\rho)}_{C_T\mathcal{C}^{1+\alpha}} \leq c(\rho)\|b - b^N\|_{C_T\mathcal{C}^{-\beta}}. \tag{8}$$

With $c(\rho)$ as in Proposition 1 and ρ_0 is large enough such that $c(\rho) > 0$ for all $\rho > \rho_0$. Then for all $t \in [0, T]$

$$\|u^N(t) - u(t)\|_{L^\infty} \leq \kappa_\rho\|b - b^N\|_{C_T\mathcal{C}^{-\beta}} \tag{9}$$

$$\|\nabla u^N(t) - \nabla u(t)\|_{L^\infty} \leq \kappa_\rho\|b - b^N\|_{C_T\mathcal{C}^{-\beta}} \tag{10}$$

with $\kappa_\rho = c \cdot c(\rho) \cdot e^{\rho T}$.

Proof. First let us prove Eq. (9).

Let $t \in [0,T]$, and see that since $u, u^N \in C_T\mathcal{C}^{(1+\beta)+}$ there exists $\alpha > \beta$ such that $u, u^N \in C_T\mathcal{C}^{1+\alpha}$, then for any $f \in \mathcal{C}^{1+\alpha}$ we have

$$\|f\|_{C^{1+\alpha}} \leq c\left(\sup_{x\in\mathbb{R}^d}|f(x)| + \sup_{x\neq y\in\mathbb{R}^d}\frac{|\nabla f(x)-\nabla f(y)|}{|x-y|^\alpha}\right) \tag{11}$$

so we have

$$\begin{aligned} \|u^N(t)-u(t)\|_{L^\infty} &= \sup_{x\in\mathbb{R}^d}|u^N(t,x)-u(t,x)| \\ &\leq c\|u^N(t)-u(t)\|_{\mathcal{C}^{\alpha+1}} \end{aligned} \tag{12}$$

Moreover, using the (ρ)-equivalent norm

$$\|f\|_{\mathcal{C}^{1+\alpha}} = \sup_{t\in[0,T]} e^{-\rho(T-t)}\|f(t)\|_{\mathcal{C}^{1+\alpha}}, \tag{13}$$

and Eq. (8) we see that

$$\begin{aligned} \left\|u^N-u\right\|_{C_T\mathcal{C}^{1+\alpha}} &= \sup_{t\in[0,T]}\left\|u^N-u\right\|_{\mathcal{C}^{1+\alpha}} \\ &= \sup_{t\in[0,T]} e^{\rho(T-t)}e^{-\rho(T-t)}\left\|u^N-u\right\|_{\mathcal{C}^{1+\alpha}} \\ &\leq e^{\rho T}\sup_{t\in[0,T]} e^{-\rho(T-t)}\left\|u^N-u\right\|_{\mathcal{C}^{1+\alpha}} \\ &= e^{\rho T}\left\|u^N-u\right\|^{(\rho)}_{C_T\mathcal{C}^{1+\alpha}}. \end{aligned} \tag{14}$$

Plugging Eq. (14) into Eq. (12)

$$\begin{aligned} \|u^N(t)-u(t)\|_{L^\infty} &\leq c\|u^N(t)-u(t)\|_{\mathcal{C}^{\alpha+1}} \\ &\leq \sup_{t\in[0,T]} c\left\|u^N(t)-u(t)\right\|_{\mathcal{C}^{\alpha+1}} \\ &= c\left\|u^N-u\right\|_{C_T\mathcal{C}^{\alpha+1}} \\ &\leq ce^{\rho T}\left\|u^N-u\right\|^{(\rho)}_{C_T\mathcal{C}^{\alpha+1}}. \end{aligned} \tag{15}$$

And finally by Eq. (8)

$$\left\|u^N(t)-u(t)\right\|_{L^\infty} \leq c\cdot c(\rho)\cdot e^{\rho T}\left\|b^N-b\right\|_{C_T\mathcal{C}^{-\beta}} \tag{16}$$

which proves Eq. (9).

For Eq. (10) recall that if $f \in \mathcal{C}^{1+\alpha}$ then $\nabla f \in \mathcal{C}^\alpha$. Also, by Bernstein inequality [3, Eqn. (9)]

$$\|\nabla f\|_\alpha \leq c\|f\|_{\infty+\alpha}. \tag{17}$$

Using the equivalent norm

$$\|f\|_{C^{1+\alpha}} \leq c\left(\sup_{x\in\mathbb{R}^d}|f(x)| + \sup_{x\in\mathbb{R}^d}|\nabla f(x)| + \sup_{x\neq y\in\mathbb{R}^d}\frac{|\nabla f(x)-\nabla f(y)|}{|x-y|^\alpha}\right) \tag{18}$$

we can see that

$$\left\|\nabla u^N(t) - \nabla u(t)\right\|_{L^\infty} \leq c\left\|u^N(t) - u(t)\right\|_{\mathcal{C}^{1+\alpha}}. \tag{19}$$

And usign the same bounds that we used above for $c\left\|u^N(t) - u(t)\right\|_{\mathcal{C}^{1+\alpha}}$ this point follows.

□

4 Bound for the difference of the auxiliary functions

This is the adaptation of result [1, Lemma 5.3].

Proposition 3. *Take $\rho > \rho_0$ as in Proposition 1, $N \to \infty$, κ_ρ from Proposition 2, and $\beta \in (0, 1/2)$, then we have*

$$\sup_{(t,x)\in[0,T]\times\mathbb{R}} \left|\psi(t,x) - \psi^N(t,x)\right| \leq 2\kappa_\rho\left\|b - b^N\right\|_{C_T\mathcal{C}^{-\beta}} \tag{20}$$

Proof. Recall the definition of $\psi, \phi \in C_T\mathcal{C}^1$

$$\phi(t,x) := x + u(t,x) \tag{21}$$

$$\psi(t,\cdot) = \phi^{-1}(t,\cdot). \tag{22}$$

Note that

$$u(y) = \int_0^1 \nabla u(\alpha y) y d\alpha + u(0). \tag{23}$$

From there we have

$$u(t,y) - u(t,y') = \int_0^1 \nabla u(t, \alpha(y-y'))(y-y')d\alpha \tag{24}$$

and therefore

$$|u(t,y) - u(t,y')| \geq \left(\int_0^1 |\nabla u(t,\alpha(y-y'))|^2 d\alpha\right)^{1/2} |y-y'|, \tag{25}$$

and by 2 we finally have

$$\begin{aligned} |u(t,y) - u(t,y')| &\leq \left(\frac{1}{4}\int_0^1 d\alpha\right)^{1/2} |y-y'| \\ |u(t,y) - u(t,y')|^2 &\leq \frac{1}{4}|y-y'|^2 \end{aligned} \tag{26}$$

□

continue from page three in notes

5 Bound for the local time at zero of the solution to the SDEs

We need a bound for $\mathbb{E}[L^0_T(Y^N - Y)]$, for Sobolev spaces, this is result [1, Proposition 5.4] we present it here for the solutions to the SDE blonging to the appropriate Besov spaces.

Proposition 4. *Let $b \in C_T\mathcal{C}^{-\beta}$ and $b^N \to b$ in $C_T\mathcal{C}^{-\beta}$ as $N \to \infty$ for $\beta \in (0, \frac{1}{4})$ and for any $\alpha > \beta$*

Proof. Recall that Y^N, Y are solutions to the SDEs

$$Y_t = y_0 + \lambda \int_0^t u(s, \psi(s, Y_s))ds + \int_0^t (\nabla u(s, \psi(s, Y_t)) + 1)dW_s \tag{27}$$

and

$$Y_t^N = y_0^N + \lambda \int_0^t u^N(s, \psi^N(s, Y_s^N))ds + \int_0^t (\nabla u^N(s, \psi^N(s, Y_t^N)) + 1)dW_s \tag{28}$$

so that the difference $Y^N - Y$ is

$$\begin{aligned} Y^N - Y_t &= (y_0^N + \lambda \int_0^t u^N(s, \psi^N(s, Y_s^N))ds + \int_0^t (\nabla u^N(s, \psi^N(s, Y_t^N)) + 1)dW_s) \\ &\quad - (y_0 + \lambda \int_0^t u(s, \psi(s, Y_s))ds + \int_0^t (\nabla u(s, \psi(s, Y_t)) + 1)dW_s) \\ &= (y_0^N - y_0) + \lambda \int_0^t (u^N(s, \psi^N(s, Y_s^N)) - u(s, \psi(s, Y_s)))ds \\ &\quad - \int_0^t (\nabla u^N(s, \psi^N(s, Y_t^N)) - \nabla u(s, \psi(s, Y_t)))dW_s, \end{aligned} \tag{29}$$

and using Lemma 1 we have the following bound

$$\begin{aligned} \mathbb{E}[L_t^0(Y^N - Y)] &\le 4\epsilon + 1 \\ &\quad - 2(1+\lambda)\mathbb{E}\Big[\int_0^t \Big(\mathbb{1}_{\{Y_s^N - Y_s \in (0,\epsilon)\}} + \mathbb{1}_{\{Y_s^N - Y_s \ge \epsilon\}} e^{1 - \frac{Y_s^N - Y_s}{\epsilon}}\Big)\big(u^N(s, \psi^N(s, Y_s^N)) - u(s, \psi(s, Y_s))\big)ds\Big] \\ &\quad + \frac{1}{\epsilon}\mathbb{E}\Big[\int_0^t \mathbb{1}_{\{Y_s^N - Y_s > \epsilon\}} e^{1 - \frac{Y_s^N - Y_s}{\epsilon}} \big(\nabla u^N(s, \psi^N(s, Y_s^N)) - \nabla u(s, \psi(s, Y_s))\big)^2 ds\Big]. \end{aligned} \tag{30}$$

add the explanation of why to drop the difussion term

For the second and third terms of Eq. (30) let us bound the factors involving the differences of u, u^N and $\nabla u, \nabla u^N$.

First, for u, u^N adding and subtracting terms and using triangle inequality we have

$$\begin{aligned} \big|u^N(s, \psi^N(s, Y_s^N)) - u(s, \psi(s, Y_s))\big| &\le \big|u^N(s, \psi^N(s, Y_s^N)) - u(s, \psi^N(s, Y_s^N))\big| \\ &\quad + \big|u(s, \psi^N(s, Y_s^N)) - u(s, \psi(s, Y_s^N))\big| \\ &\quad + \big|u(s, \psi(s, Y_s^N)) - u(s, \psi(s, Y_s))\big|. \end{aligned} \tag{31}$$

□

The terms in the right hand side will be bounded as follows:

- For the first term, by Proposition 2

$$\left|u^N(s,\psi^N(s,Y_s^N)) - u(s,\psi^N(s,Y_s^N))\right| \le \left\|u^N(s) - u(s)\right\|_{L^\infty} \le \kappa_\rho \left\|b - b^N\right\|_{C_T\mathcal{C}^{-\beta}}, \tag{32}$$

- for the second term, observe that u, u^N are $\frac{1}{2}$-Lipschitz and by Proposition 3 we get

$$\left|u(s,\psi^N(s,Y_s^N)) - u(s,\psi(s,Y_s^N))\right| \le \frac{1}{2}\left|\psi^N(s,Y_s^N) - \psi(s,Y_s^N)\right| \le \kappa_\rho \left\|b^N - b\right\|_{C_T\mathcal{C}^{-\beta}}, \tag{33}$$

- and for the final term, note that ψ, ψ^N are 2-Lipschitz
  so that

$$\left|u(s,\psi(s,Y_s^N)) - u(s,\psi(s,Y_s))\right| \le \frac{1}{2}\left|\psi(s,Y_s^N) - \psi(s,Y_s)\right| \le \left|Y_s^N - Y_s\right|. \tag{34}$$

So that the following bound holds

$$\left|u^N(s,\psi^N(s,Y_s^N)) - u(s,\psi(s,Y_s))\right| \le 2\kappa_\rho \left\|b^N - b\right\|_{C_T\mathcal{C}^{-\beta}}, + \left|Y_s^N - Y^N\right|. \tag{35}$$

Now for the third term in Eq. (30) by adding and subtracting terms and using the triangle inequality

$$\begin{aligned}\left|\nabla u^N(s,\psi^N(s,Y_s^N)) - \nabla u(s,\psi(s,Y_s))\right| \le{}& \left|\nabla u^N(s,\psi^N(s,Y_s^N)) - \nabla u(s,\psi^N(s,Y_s^N))\right| \\ &+ \left|\nabla u(s,\psi^N(s,Y_s^N)) - \nabla u(s,\psi(s,Y_s^N))\right| \quad . \\ &+ \left|\nabla u(s,\psi(s,Y_s^N)) - \nabla u(s,\psi(s,Y_s))\right|\end{aligned} \tag{36}$$

The terms on the right hand side will be bounded as follows:

- For the first term we use Proposition 2 and we have

$$\begin{aligned}\left|\nabla u^N(s,\psi^N(s,Y_s^N)) - \nabla u(s,\psi^N(s,Y_s^N))\right| &\le \left\|\nabla u^N(s) - \nabla u(s)\right\|_{L^\infty} \\ &\le \kappa_\rho \left\|b - b^N\right\|_{C_T\mathcal{C}^{-\beta}},\end{aligned} \tag{37}$$

  for the second term see that $\nabla u, \nabla u^N$ are α-Hölder continuous and using Proposition 3 we have

$$\begin{aligned}\left|\nabla u(s,\psi^N(s,Y_s^N)) - \nabla u(s,\psi(s,Y_s^N))\right| &\le \left|\psi^N(s,Y_s^N) - \psi(s,Y_s^N)\right|^\alpha \|u\|_{C_T\mathcal{C}^{1+\alpha}} \\ &\le (2\kappa_\rho \left\|b^N - b\right\|_{C_T\mathcal{C}^{-\beta}})^\alpha \|u\|_{C_T\mathcal{C}^{1+\alpha}}.\end{aligned} \tag{38}$$

Therefore we get the bound

$$\begin{aligned} \left|\nabla u^N(s, \psi^N(s, Y_s^N)) - \nabla u(s, \psi(s, Y_s))\right| \leq \kappa_\rho \|b - b^N\|_{C_T\mathcal{C}^{-\beta}} & \\ + 2^\alpha \kappa_\rho^\alpha \|b^N - b\|^\alpha_{C_T\mathcal{C}^{-\beta}} \|u\|_{C_T\mathcal{C}^{1+\alpha}} & . \\ + \left|\nabla u(s, \psi(s, Y_s^N)) - \nabla u(s, \psi(s, Y_s))\right| & \end{aligned} \quad (39)$$

Using the bounds for Eq. (35) and Eq. (39) and the inequality

$$(x_1 + \cdots + x_k)^2 \leq k(x_1 + \cdots + x_k), \quad (40)$$

for some k, we get

$$\begin{aligned} \mathbb{E}[L_t^0(Y^N - Y)] \leq 4\epsilon & \\ + 4(1+\lambda)\left(2\kappa_\rho \|b^N - b\|_{C_T\mathcal{C}^{-\beta}} t + \mathbb{E}\left[\int_0^t \left|Y_s^N - Y^N\right| ds\right]\right) & \\ + \frac{1}{\epsilon} 3t \|b^N - b\|_{C_T\mathcal{C}^{-\beta}} \left(\kappa_\rho^2 \|b^N - b\|_{C_T\mathcal{C}^{-\beta}} + 4(2\kappa_\rho^2 \|b^N - b\|)\right) & \end{aligned} \quad (41)$$

6 Convergence rate of the solution to the regularised SDE and the original

References

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