

Stochastic approximations of set-valued dynamical systems: Convergence with positive probability to an attractor *

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Abstract

A successful method to describe the asymptotic behavior of a discrete time stochastic process governed by some recursive formula is to relate it to the limit sets of a well chosen mean differential equation. Under an attainability condition, convergence to a given attractor of the flow induced by this dynamical system was proved to occur with positive probability (Benaïm, 1999) for a class of Robbins Monro algorithms. Benaïm et al. (2005) generalised this approach for stochastic approximation algorithms whose average behavior is related to a differential inclusion instead. We pursue the analogy by extending to this setting the result of convergence with positive probability to an attractor.

Key words: Stochastic approximations, set-valued dynamical systems, attractor, game theory, Markovian fictitious play

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1 Introduction

1.1 Settings and bibliography

Stochastic approximation algorithms were born in the early 50s through the work of Robbins and Monro [21] and Kiefer and Wolfowitz [16]. Consider a discrete time stochastic process $(x_n)_{n \geq 0}$ defined by the following recursive formula:

$$x_{n+1} - x_n = \gamma_{n+1} (F(x_n) + U_{n+1}), \quad (1)$$

where $F : \mathbb{R}^m \rightarrow \mathbb{R}^m$ is a Lipschitz function, $(\gamma_n)_n$ is a positive decreasing sequence and $(U_n)_n$ a sequence of \mathbb{R}^m -valued random variables defined on a probability space (Ω, \mathcal{F}, P) , adapted to some filtration $(\mathcal{F}_n)_n \subset \mathcal{F}$. In order to describe the limit behavior of the sample paths $(x_n(\omega))_n$, a natural

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idea is to compare them to the solution curves of the dynamical system induced by the ordinary differential equation

$$\frac{dx}{dt} = F(x). \quad (2)$$

This is the celebrated method of ordinary differential equation (ODE) which was introduced by Ljung in [20]. Heuristically, one can think of (1) as a kind of Cauchy-Euler approximation scheme for numerically solving (2) with step size $(\gamma_n)_n$ and an added noise $(U_n)_n$. We could reasonably expect that, under appropriate assumptions on $(\gamma_n)_n$ and if the noise $(U_n)_n$ vanishes, the asymptotic behaviors of $(x_n)_n$ and the ODE are closely related.

Thereafter, the method was studied and developed by many people (see Kushner and Clark [18], Benveniste et al [9], Duflo [12] or Kushner and Yin [19]). Originally, only simple dynamics were considered, for example the negative of the gradient of a cost function. However, it appears in several situations, for example, learning models or game theory, that the corresponding vector field may be more complex.

Benaïm and Hirsch have conducted, in a series of papers (essentially [5] and [3]), a thorough study of this method. They proved that the asymptotic behavior of stochastic approximation process can be described with a great deal of generality through the study of the asymptotics of the ODE. One of the main results is the characterization of limit sets $(x_n(\omega))_n$ via the flow induced by F , in the sense that, almost surely, these sets are compact, invariant and contain no proper attractor for the deterministic flow (this is the notion of *internal chain recurrence* in the sense of Conley [11], see also Bowen [10]).

Now, let $F : \mathbb{R}^m \rightrightarrows \mathbb{R}^m$ be a sufficiently regular set-valued map and consider some discrete time stochastic processes $(x_n)_{n \geq 0}$ satisfying the following recursive formula:

$$x_{n+1} - x_n - \gamma_{n+1}U_{n+1} \in \gamma_{n+1}F(x_n), \quad (3)$$

where $(\gamma_n)_n$ is a positive decreasing sequence and $(U_n)_n$ a sequence of \mathbb{R}^m -valued random variables defined on a probability space (Ω, \mathcal{F}, P) .

In [6], Benaïm, Hofbauer and Sorin have generalized the ODE method to the algorithms given by (3) and extended the characterization of limits set in the sense that they are again, under certain assumptions on the step size and the noise, connected and attractor free for the set-valued dynamical system induced by the differential inclusion

$$\frac{dx}{dt} \in F(x). \quad (4)$$

This generalization allows us to extend this technique to a much wider class of problems arising, for example, in economics or game theory (see Benaïm, Hofbauer and Sorin [7]).

In this paper, we pursue the analogy between the ODE method and the differential inclusion method. The aim is to extend to the case of differential inclusions, the result of Benaïm (see theorem 7.3 in [4]) which guarantees that, under certain assumptions on the step size and the noise, the stochastic approximation process converges with positive probability to a given attractor of the set-valued dynamical system induced by F .

The organization of the paper is as follows. In section 1.2, we define a standard set-valued map and introduce the crucial notion of attainability so as to state a simple version of the main result. In section 2, we introduce the different notions of internal chain transitivity, asymptotic pseudotrajectories and perturbed solutions. Our main assumption (hypothesis 2.7) is given, the convergence result is stated in full generality and we define a generalised stochastic approximation process which satisfies the above assumption. An example of adaptive learning process to which our results may be applied is given in section 3. Finally, the proof of a crucial result needed in our study is postponed to section 4.

1.2 The main result, a simple version

In the following, $M \subset \mathbb{R}^m$ is a compact set.

Definition 1.1. [Standard set-valued map] A correspondance $F : \mathbb{R}^m \rightrightarrows \mathbb{R}^m$ is said to be standard if it satisfies the following assumptions:

- for any $x \in \mathbb{R}^m$, $F(x)$ is a non empty, compact and convex set of \mathbb{R}^m ,
- F is closed, which means that its graph

$$\text{Gr}(F) := \{(x, y) \in \mathbb{R}^m \times \mathbb{R}^m \mid y \in F(x)\}$$

is closed,

- there exists $c > 0$ such that

$$\sup_{z \in F(x)} \|z\| \leq c(1 + \|x\|).$$

Under the above assumptions, it is well known (see Aubin and Cellina [1]) that (4) admits at least one solution (i.e. an absolutely continuous mapping $\mathbf{x} : \mathbb{R} \rightarrow \mathbb{R}^m$ such that $\dot{\mathbf{x}}(t) \in F(\mathbf{x}(t))$ for almost every t) through any initial point.

We call S_x the set of solutions with initial condition $\mathbf{x}(0) = x$. The set-valued dynamical system induced by the differential inclusion will be denoted $\Phi = (\Phi_t)_{t \in \mathbb{R}}$. To any $x \in \mathbb{R}^m$, it associates the non empty set

$$\Phi_t(x) := \{\mathbf{x}(t) \mid \mathbf{x} \in S_x\}.$$

Finally, $S_\Phi := \cup_x S_x$ is the set of all solution curves. In order to understand the main result, recall some classical definitions about the set-valued dynamics.

Definition 1.2. A non empty compact set $A \subset \mathbb{R}^m$ is called an attractor for Φ , provided it is invariant (i.e. for all $x \in A$, there exists a solution \mathbf{x} to (4) with $\mathbf{x}(0) = x$ and such that $\mathbf{x}(\mathbb{R}) \subset A$) and that there is a neighborhood U of A with the property that, for every $\epsilon > 0$, there exists $t_\epsilon > 0$ such that

$$\Phi_t(U) \subset N^\epsilon(A)$$

for all $t \geq t_\epsilon$, where $N^\epsilon(A)$ is the ϵ -neighborhood of A . An open set U with this property is called a fundamental neighborhood of A .

Definition 1.3. Let $A \subset \mathbb{R}^m$ be an attractor for the set-valued dynamical system. The basin of attraction of A is the set

$$\mathcal{B}(A) := \{x \in \mathbb{R}^m : \Phi_{[0, +\infty[}(x) \text{ bounded and } \omega_\Phi(x) \subset A\},$$

where $\omega_\Phi(x) = \bigcap_{t \geq 0} \overline{\Phi_{[t, \infty[}(x)}$ is the omega limit set of the point x .

Now consider a discrete time stochastic process $(x_n)_n$ in M defined by (3), and satisfying the following assumptions:

- (i) For all $c > 0$,

$$\sum_n e^{-c/\gamma_n} < \infty,$$

- (ii) $(U_n)_n$ is uniformly bounded and

$$\mathbb{E}(U_{n+1} \mid \mathcal{F}_n) = 0,$$

(iii) F is a standard set-valued map.

Set $\tau_n := \sum_{i=1}^n \gamma_i$ and $m(t) := \sup\{j \mid \tau_j \leq t\}$. We call X the continuous time affine interpolated process induced by $(x_n)_n$ and $\bar{\gamma}$ the piecewise constant deterministic process induced by $(\gamma_n)_n$:

$$X(\tau_i + s) = x_i + s \frac{x_{i+1} - x_i}{\gamma_{i+1}}, \text{ for } s \in [0, \gamma_{i+1}] \text{ and } \bar{\gamma}(\tau_i + s) := \gamma_{i+1} \text{ for } s \in [0, \gamma_{i+1}[,$$

and consider its limit set

$$\mathcal{L}(X) := \bigcap_{t \geq 0} \overline{\{X(s) : s \geq t\}}.$$

The following attainability condition is crucial to show that X converges with positive probability to a given attractor.

Definition 1.4. A point $p \in M$ is attainable if, for any $t > 0$ and any neighborhood U of p ,

$$\mathbb{P}(\exists s \geq t : X(s) \in U) > 0.$$

We call $Att(X)$ the set of attainable points by X . The following statement is a special case of our main result, Theorem 2.15.

Theorem 1.5. Let $A \subset M$ be an attractor for Φ with basin of attraction $\mathcal{B}(A)$. If $Att(X) \cap \mathcal{B}(A) \neq \emptyset$ then

$$P(\mathcal{L}(X) \subset A) > 0.$$

Heuristically, this means that if the set of attainable points of the process meets the basin of attraction of a given attractor A , then there is convergence with positive probability toward A .

2 Convergence with positive probability

2.1 Set-valued dynamical systems relative to a differential inclusion.

We recall here some definitions and results due to Benaïm et al (see [6]).

Let $F : \mathbb{R}^m \rightrightarrows \mathbb{R}^m$ be a standard set-valued map and Φ be the set-valued dynamical system associated to the differential inclusion

$$\frac{d\mathbf{x}}{dt} \in F(\mathbf{x}) \tag{5}$$

The notion of *internally chain transitive set* (ICT set) was introduced by Benaïm and Hirsch in [5] to analyse certain perturbations of the flow relative to an ODE. This is an extension of the notion of chain recurrence due to Conley [11]. The concept of ICT sets was extended to differential inclusions by Benaïm et al. in [6].

We refer to this last reference for an accurate description of ICT sets. Here, we only need the following property (see [6], Proposition 3.20): an internally chain transitive set L is invariant, compact and the restricted set-valued dynamical system $\Phi|_L$ admits no proper attractor (i.e. no attractor distinct from L). The following result is proved in [6] (see Theorem 3.23)

Theorem 2.1. Let L be an internally chain transitive set and A be an attractor for Φ with basin of attraction $\mathcal{B}(A)$. Then

$$\mathcal{B}(A) \cap L \neq \emptyset \Rightarrow L \subset A.$$

The space $\mathcal{C}(\mathbb{R}_+, \mathbb{R}^m)$ of continuous paths, endowed with the metric

$$\mathbf{D}(\mathbf{x}, \mathbf{x}') := \sum_{k=1}^{\infty} \frac{1}{2^k} \min \left(\sup_{u \in [0, k]} \|\mathbf{x}(u) - \mathbf{x}'(u)\|, 1 \right)$$

is complete. A continuous map $X : \mathbb{R}_+ \rightarrow \mathbb{R}^m$ is an *asymptotic pseudotrajectory* (APT) of the set-valued dynamical system $(\Phi_t)_{t \geq 0}$ if, for any $T > 0$,

$$\lim_{t \rightarrow +\infty} \inf_{\mathbf{z} \in S_\Phi} \|X(t + \cdot) - \mathbf{z}(\cdot)\|_{[0, T]} = 0,$$

where $\|\cdot\|_{[0, T]}$ denotes the uniform norm on $[0, T]$. Heuristically this means that, for any $T > 0$, the curve joining $X(t)$ to $X(t+T)$ shadows the trajectory of some solution with arbitrary accuracy, provided t is large enough.

A fundamental property of asymptotic pseudotrajectories is that, if X is a bounded APT, then its limit set $\mathcal{L}(X)$ is internally chain transitive (see [6], Theorem 4.3). Consequently, by Theorem 2.1, we have

Corollary 2.2. *Let X be an asymptotic pseudotrajectory of the set-valued dynamical system and A an attractor for Φ . If $\mathcal{L}(X)$ meets the basin of attraction of A , then it belongs to A .*

Let δ be a positive real number. Then F^δ is the set-valued map defined by

$$F^\delta(x) := \{y \mid \exists z \in B(x, \delta) \text{ such that } d(y, F(z)) < \delta\}. \quad (6)$$

Definition 2.3. *Let $\delta : \mathbb{R}_+^* \rightarrow \mathbb{R}_+^*$ and $\overline{U} : \mathbb{R}_+ \rightarrow \mathbb{R}^m$. A continuous function $\mathbf{y} : \mathbb{R}_+ \rightarrow \mathbb{R}^m$ is a $(\delta(\cdot), \overline{U}(\cdot))$ -perturbed solution of the differential inclusion (5) if*

- (i) \mathbf{y} is absolutely continuous,
- (ii) $\delta(t) \downarrow_{t \rightarrow +\infty} 0$ and, for almost every $t > 0$,

$$\frac{d\mathbf{y}(t)}{dt} - \overline{U}(t) \in F^{\delta(t)}(\mathbf{y}(t)),$$

- (iii) \overline{U} is locally integrable and such that, for any $T > 0$,

$$\lim_{t \rightarrow +\infty} \sup_{0 \leq v \leq T} \left\| \int_t^{t+v} \overline{U}(s) ds \right\| = 0. \quad (7)$$

We recall the following theorem due to Benaïm et al (see [6] Theorem 4.2).

Theorem 2.4. *Any bounded perturbed solution of the differential inclusion (5) is an asymptotic pseudotrajectory of the set-valued dynamical system Φ .*

2.2 A deterministic result

For any application $X : \mathbb{R}_+ \rightarrow M$ and $T > 0$, we define the quantity

$$d_X(T) := \sup_{k \in \mathbb{N}} \inf_{\mathbf{z} \in S_\Phi} \|\mathbf{z}(\cdot) - X(kT + \cdot)\|_{[0, T]}.$$

The following characterization of the basin of attraction will be useful.

Lemma 2.5. *Given an attractor A , the basin of attraction of A is the union of all fundamental neighborhoods of A .*

Proof. Any fundamental neighborhood is trivially included into $\mathcal{B}(A)$. Conversely, let $x \in \mathcal{B}(A)$ and U_0 be a given fundamental neighborhood of A : for any $\varepsilon > 0$, there exists $t_\varepsilon^0 > 0$ such that

$$\Phi_t(U_0) \subset N^\varepsilon(A), \quad \forall t \geq t_\varepsilon^0.$$

Pick $\gamma > 0$ such that $N^{2\gamma}(A) \subset U_0$. There exists $T > 0$ such that $\Phi_T(x) \subset N^\gamma(A)$. Otherwise, there would exist sequences $(\mathbf{z}_n)_n \subset S_x$ and $t_n \uparrow +\infty$ such that $\mathbf{z}_n(t_n) \in (N^\gamma(A))^c$, which contradicts the fact that $\omega_\Phi(x)$ is bounded and contained in A .

Finally, by closedness of the set-valued map $x \mapsto \Phi_T(x)^1$, there exists $r > 0$ such that $\Phi_T(B(x, r)) \subset N^{2\gamma}(A) \subset U_0$. The set $U := U_0 \cup B(x, r)$ is a fundamental neighborhood of A since, for any $\varepsilon > 0$,

$$\Phi_t(B(x, r)) \subset N^\varepsilon(A), \quad \forall t \geq t_\varepsilon^0 + T,$$

and the proof is complete. ■

Assume now that X is an APT of the set-valued dynamical system $(\Phi_t)_{t \geq 0}$. The following lemma is the extension to differential inclusions of Lemma 6.8 in Benaïm [4].

Lemma 2.6. *Let $A \subset \mathbb{R}^m$ be an attractor for the set-valued dynamical system Φ , with basin of attraction $\mathcal{B}(A)$. Then, for any compact set $K \subset \mathcal{B}(A)$, there exist positive real numbers $\alpha(K)$ and $T(K)$ such that*

$$(X(0) \in K \text{ and } d_X(T(K)) < \alpha(K)) \Rightarrow \mathcal{L}(X) \subset A.$$

Proof. Let W be an open set with compact closure such that

$$A \cup K \subset W \subset \overline{W} \subset \mathcal{B}(A).$$

There exists $\alpha > 0$ such that $N^{3\alpha}(A) \subset W$ and $N^\alpha(K) \subset W$. Since \overline{W} is included in the basin of attraction of A , there exists a fundamental neighborhood which contains W ; hence we can find a positive number T (which depends on α and W) such that

$$\Phi_{[T, +\infty[}(W) \subset N^\alpha(A).$$

Assume now that $X(0) \in K$ and $d_X(T) < \alpha$. There exists a solution \mathbf{z}^1 which shadows X on $[0, T]$; in particular,

$$\mathbf{z}^1(0) \in N^\alpha(X(0)) \subset W \text{ and } X(T) \in N^\alpha(\mathbf{z}^1(T)).$$

By definition of T , $\mathbf{z}^1(T) \in N^\alpha(A)$, which means that $X(T) \in N^{2\alpha}(A) \subset W$.

By a recursive argument, we show that the sequence $(X(kT))_{k \geq 1}$ belongs to the set $N^{2\alpha}(A)$. Assume that $X(kT) \in N^{2\alpha}(A)$. Then, there exists a solution $\mathbf{z}^{k+1}(\cdot)$ which is α -close of $X(kT + \cdot)$ on $[0, T]$: in particular,

$$\mathbf{z}^{k+1}(0) \in N^\alpha(X(kT)) \subset N^{3\alpha}(A) \subset W \text{ and } X(kT + T) \in N^\alpha(\mathbf{z}^{k+1}(T)) \subset N^{2\alpha}(A).$$

Consequently, the limit set $\mathcal{L}(X)$ is contained in $W \subset \mathcal{B}(A)$. Hence, $\mathcal{L}(X) \subset A$ by Corollary 2.2. ■

¹This is an easy consequence of Definition 1.1.

2.3 Stochastic processes

In the following, $(X(t))_{t \geq 0}$ will be a continuous time \mathbb{R}^m -valued stochastic process, adapted to some non decreasing sequence $(\mathcal{F}_t)_t$ of sub sigma algebras of \mathcal{F} .

Hypothesis 2.7. *There exists a map $\omega : \mathbb{R}_+^3 \rightarrow \mathbb{R}_+$ such that, for any $\alpha > 0$ and $T > 0$,*

$$\mathbb{P} \left(\sup_{s \geq t} \inf_{\mathbf{z} \in S_\Phi} \|\mathbf{z}(\cdot) - X(s + \cdot)\|_{[0, T]} \geq \alpha \mid \mathcal{F}_t \right) \leq \omega(t, \alpha, T) \downarrow_{t \rightarrow +\infty} 0 \quad \text{almost surely.} \quad (8)$$

Hypothesis 2.7 is a technical assumption, slightly stronger than supposing that X is almost surely an APT. Recall that $\text{Att}(X)$ is the set of attainable points by X .

Theorem 2.8. *Let A be an attractor and $(X(t))_{t \geq 0}$ be an adapted process satisfying hypothesis 2.7. Then, if $\text{Att}(X) \cap \mathcal{B}(A) \neq \emptyset$, we have*

$$\mathbb{P}(\mathcal{L}(X) \subset A) > 0.$$

Proof. We adapt the proof of Theorem 7.3 in Benaïm [4]. Let U be an open set included in $\mathcal{B}(A)$ and call $K = \overline{U}$. By Lemma 2.6 there exist $\alpha(K)$ and $T(K)$ such that

$$(X(0) \in K \text{ and } d_X(T(K)) < \alpha(K)) \Rightarrow \mathcal{L}(X) \subset A.$$

Let t be a positive irrational number such that $\omega(t, \alpha, T) < 1$ and denote $t_n(k) = \frac{k}{2^n}$ for n and k in \mathbb{N} . We define the stopping time

$$\tau_n := \inf_{k \in \mathbb{N}} \{t_n(k) \mid X(t_n(k)) \in U, t_n(k) \geq t\}.$$

On the intersection of the events $\{\tau_n < \infty\}$ and $\{\sup_{s \geq \tau_n} \inf_{\mathbf{z} \in S_\Phi} \|\mathbf{z}(\cdot) - X(s + \cdot)\|_{[0, T]} \leq \alpha\}$ the set $\mathcal{L}(X)$ is included in A . Consequently, we have

$$\begin{aligned} \mathbb{P}(\mathcal{L}(X) \subset A) &\geq \sum_{k \geq [2^n t] + 1} \mathbb{E} \left(\mathbb{P} \left(\sup_{s \geq \tau_n} \inf_{\mathbf{z} \in S_\Phi} \|\mathbf{z}(\cdot) - X(s + \cdot)\|_{[0, T]} \leq \alpha \mid \mathcal{F}_{t_n(k)} \right) \mathbb{I}_{\tau_n = t_n(k)} \right) \\ &\geq \sum_{k \geq [2^n t] + 1} (1 - \omega(t_n(k), \alpha, T)) \mathbb{P}(\tau_n = t_n(k)) \geq (1 - \omega(t, \alpha, T)) \mathbb{P}(\tau_n < +\infty), \end{aligned}$$

since $\omega(t_n(k), \alpha, T) \leq \omega(t, \alpha, T)$, $\forall k \geq [2^n t] + 1$. On the other hand, the sequence of events $\{\tau_n < +\infty\}$ is increasing and we have

$$\lim_{n \rightarrow +\infty} \uparrow \{\tau_n < +\infty\} = \cup_n \{\tau_n < +\infty\} = \{\exists s \geq t \mid X(s) \in U\}.$$

Now take an attainable point $p \in \mathcal{B}(A)$ and U a neighborhood of p , such that $\overline{U} \subset \mathcal{B}(A)$. We have

$$\mathbb{P}(\mathcal{L}(X) \subset A) \geq (1 - \omega(t, \alpha, T)) \mathbb{P}(\exists s \geq t \mid X(s) \in U) > 0,$$

and the proof is complete. \blacksquare

Now, we consider a compact set $M \subset \mathbb{R}^m$ and a standard set-valued map $F : \mathbb{R}^m \rightrightarrows \mathbb{R}^m$. Let $T > 0$. Denote $\Phi^T(M) := \overline{\bigcup_{s \in [0, T]} \Phi_s(M)}$, $\|F\| = \sup_{x \in \Phi^T(M)} \sup_{y \in F(x)} \|y\|$ and let us define the compact set

$$K_C := K_{(\|F\|, C)} = \{\mathbf{y} \in \text{Lip}([0, T], \mathbb{R}^m) \mid \text{Lip}(\mathbf{y}) \leq \|F\| + C + 1, \mathbf{y}(0) \in M\},$$

where C is a positive constant and $\text{Lip}([0, T], \mathbb{R}^m)$ is the set of Lipschitz functions from $[0, T]$ to \mathbb{R}^m .

Remark 2.9. K_C is appropriate to our situation since it contains every solution curve, restricted to an interval of length T and any $(\delta(\cdot), \overline{U}(\cdot))$ -perturbed solution of the differential inclusion, with $\sup_{t \in [0, T]} \overline{U}(t) \leq C$ and $\delta \leq 1$.

For $\delta \in [0, 1]$, let us define the set-valued application (with the convention $\Lambda^0 = \Lambda$):

$$\Lambda^\delta : K_C \rightrightarrows K_C, \quad \mathbf{z} \mapsto \Lambda^\delta(\mathbf{z}), \quad (9)$$

where $\mathbf{y} \in \Lambda^\delta(\mathbf{z})$ if and only if there exists an integrable $h : [0, T] \rightarrow \mathbb{R}^m$ such that $h(u) \in F^\delta(\mathbf{z}(u)) \forall u \in [0, T]$ and

$$\mathbf{y}(\tau) = \mathbf{z}(0) + \int_0^\tau h(u) du, \quad \forall \tau \in [0, T].$$

Remark that $\text{Fix}(\Lambda) := \{\mathbf{z} \in K_C \mid \mathbf{z} \in \Lambda(\mathbf{z})\}$ is the set of the restrictions on $[0, T]$ of the solutions curves starting from M , which we denote $S_{[0, T]}$ from now on. Additionally, we call $d_{[0, T]}$ the distance associated to the uniform norm on $[0, T]$. The following lemma is an immediate consequence of Corollary 4.11, proved in the last section.

Lemma 2.10. *Let $C > 0$ and $\alpha > 0$. There exist $\varepsilon > 0$ and $\delta_0 > 0$ such that, for any $\delta < \delta_0$*

$$d_{[0, T]}(\mathbf{z}, \Lambda^\delta(\mathbf{z})) < \varepsilon \Rightarrow d_{[0, T]}(\mathbf{z}, S_{[0, T]}) < \alpha.$$

As a consequence, we obtain the following crucial result.

Proposition 2.11. *Assume that there exist a function $\delta : \mathbb{R}_+ \rightarrow \mathbb{R}_+$ converging to zero and a uniformly bounded random process $(\overline{U}(t))_{t \geq 0}$ such that $(X(t))_{t \geq 0}$ is almost surely a bounded (δ, \overline{U}) -perturbed solution of the differential inclusion (5) and such that $X(0) \in M$. If \overline{U} satisfies the following property*

$$\mathbb{P} \left(\sup_{s \geq t} \left\| \int_s^{s+\cdot} \overline{U}(u) du \right\|_{[0, T]} \geq \varepsilon \mid \mathcal{F}_t \right) \leq \omega(t, \varepsilon, T) \downarrow_{t \rightarrow +\infty} 0 \quad (10)$$

almost surely, then hypothesis 2.7 holds and Theorem 2.8 may be applied.

Proof. First, $X(\cdot)$ is almost surely an asymptotic pseudotrajectory of the set-valued dynamical system by Theorem 2.4. For Lipschitz (classical) dynamical systems, hypothesis 2.7 holds by an application of Gronwall lemma (see Benaïm [4], section 7). However, this does not adapt to our situation and this is the reason why we need Lemma 2.10. By assumption, we have almost surely

$$\frac{dX(t)}{dt} - \overline{U}(t) \in F^{\delta(t)}(X(t)), \quad \text{for almost every } t > 0.$$

Let $T > 0$. For any $\tau \in [0, T]$,

$$X(s + \tau) - \int_s^{s+\tau} \overline{U}(u) du \in X(s) + \int_0^\tau F^{\delta(s)}(X(s + u)) du.$$

Hence, $d_{[0, T]}(X(s + \cdot), \Lambda^{\delta(s)}(X(s + \cdot))) \leq \left\| \int_s^{s+\cdot} \overline{U}(u) du \right\|_{[0, T]}$ and

$$\begin{aligned} \mathbb{P} \left(\sup_{s \geq t} d_{[0, T]}(X(s + \cdot), \Lambda^{\delta(s)}(X(s + \cdot))) \geq \varepsilon \mid \mathcal{F}_t \right) &\leq \mathbb{P} \left(\sup_{s \geq t} \left\| \int_s^{s+\cdot} \overline{U}(u) du \right\|_{[0, T]} \geq \varepsilon \mid \mathcal{F}_t \right) \\ &\leq \omega(t, \varepsilon, T). \end{aligned}$$

Now let $\alpha > 0$. By Lemma 2.10 there exists $\varepsilon > 0$ (which depends on T and α) such that, for t large enough and $s \geq t$,

$$d_{[0,T]}(X(s + \cdot), S_{[0,T]}) \geq \alpha \Rightarrow d_{[0,T]}(X(s + \cdot), \Lambda^{\delta(t)}(X(s + \cdot))) \geq \varepsilon.$$

Consequently, for these choices of t and ε ,

$$\begin{aligned} \mathbb{P}\left(\sup_{s \geq t} d_{[0,T]}(X(s + \cdot), S_{[0,T]}) \geq \alpha \mid \mathcal{F}_t\right) &\leq \mathbb{P}\left(\sup_{s \geq t} d_{[0,T]}(X(s + \cdot), \Lambda^{\delta(t)}(X(s + \cdot))) \geq \varepsilon \mid \mathcal{F}_t\right) \\ &\leq \mathbb{P}\left(\sup_{s \geq t} \left\| \int_s^{s+\cdot} \bar{U}(u) du \right\|_{[0,T]} \geq \varepsilon \mid \mathcal{F}_t\right) \\ &\leq \omega(t, \varepsilon(\alpha, T), T), \end{aligned}$$

and the proof is complete. \blacksquare

Recall that a perturbed solution is an APT. The last proposition is a stochastic version of this result in the sense that the process $X(\cdot)$ is almost surely a perturbed solution, hence almost surely an APT. However, to yield the stronger property (2.7), we reinforce the assumption on U and assume (10) instead of (7).

2.4 Convergence of Stochastic approximation algorithms

We introduce here a class of stochastic approximation processes which generalize the Robbins-Monro algorithms. Under some assumptions on the step size and the noise, we prove that hypothesis 2.7 is verified and that the conclusion of Theorem 2.8 holds.

Definition 2.12 (Generalised stochastic approximation process). *Let $(U_n)_n$ be an uniformly bounded \mathbb{R}^m -valued random process, $(\gamma_n)_n$ a deterministic positive real sequence and $(F_n)_n$ a sequence of set-valued maps on \mathbb{R}^m . We say that $(x_n)_n$ is a generalised stochastic approximation process relative to the standard set-valued map F if the following assumptions are satisfied:*

(i) *we have the recursive formula*

$$x_{n+1} - x_n - \gamma_{n+1} U_{n+1} \in \gamma_{n+1} F_n(x_n),$$

(ii) *the step size satisfies*

$$\sum_n \gamma_n = +\infty, \quad \lim_n \gamma_n = 0,$$

(iii) *for all $T > 0$, we have almost surely*

$$\lim_{n \rightarrow +\infty} \sup \left\{ \left\| \sum_{i=n}^{k-1} \gamma_{i+1} U_{i+1} \right\| \mid k \text{ such that } \sum_{i=n}^{k-1} \gamma_i \leq T \right\} = 0,$$

(iv) *for all $n \geq 0$, $x_n \in M$,*

(v) *for any $\delta > 0$, there exists $n_0 \in \mathbb{N}$ such that*

$$\forall n \geq n_0, \quad F_n(x_n) \subset F^\delta(x_n).$$

In the following we will call $X = (X(t))_t$ the continuous time affine interpolated process induced by a given generalised stochastic approximation process $(x_n)_n$ (see section 1.2).

Proposition 2.13. *The process X is almost surely a (δ, \bar{U}) -perturbed solution, for some deterministic function δ , and \bar{U} the piecewise constant continuous time process associated to $(U_n)_n$:*

$$\bar{U}(t) := U_{n+1}, \quad \forall t \in [\tau_n, \tau_{n+1}[.$$

Proof. By straightforward computations (see the proof of proposition 1.3 in Benaïm et al. [6]), it is not difficult to see that almost surely, $(X(t))_t$ is a perturbed solution associated to \bar{U} and

$$\delta(t) := \inf \left\{ \delta > 0 \mid \tau_n \geq t \Rightarrow F_n(x_n) \subset F^\delta(x_n) \right\} + \bar{\gamma}(t) \left(\bar{U}(t) + c \left(1 + \sup_{x \in M} F(x) \right) \right),$$

which obviously converges to 0. ■

Remark 2.14. Recall that $m(t) = \sup\{j \mid \tau_j \leq t\}$. The condition (10) is equivalent to

$$\mathbb{P} \left(\sup_{m \geq n} \sup_{m < k \leq m(\tau_m + T)} \left\| \sum_{i=m}^{k-1} \gamma_{i+1} U_{i+1} \right\| \geq \varepsilon \mid \mathcal{F}_n \right) \leq \omega(n, \varepsilon, T) \downarrow_{n \rightarrow +\infty} 0 \text{ almost surely.} \quad (11)$$

and we use the notation $\Delta(n, T) := \sup_{n < k \leq m(\tau_n + T)} \left\| \sum_{i=n}^{k-1} \gamma_{i+1} U_{i+1} \right\|$ in the sequel.

Our main result is now stated in full generality.

Theorem 2.15. *Let $(x_n)_n$ be a stochastic approximation algorithm such that $(U_n)_n$ satisfies (11). Then, if A is an attractor relative to F , we have*

$$\text{Att}(X) \cap \mathcal{B}(A) \neq \emptyset \Rightarrow \mathbb{P}(\mathcal{L}(X) \subset A) > 0.$$

Proof. By Proposition 2.13, the conditions requested to apply Proposition 2.11 are satisfied. Hence, hypothesis 2.7 is checked and the result follows directly from Theorem 2.8. ■

In the particular case where $(U_n)_n$ is a martingale difference: $\mathbb{E}(U_{n+1} \mid \mathcal{F}_n) = 0$, (11) is satisfied under simple assumptions on the noise and step size.

Proposition 2.16. *Let $(U_n^0)_n$ be a martingale difference noise (not necessarily bounded) and assume that one of the following assumptions is satisfied:*

- 1) *There exists some $q \geq 2$ such that*

$$\sum \gamma_n^{1+q/2} < +\infty \text{ and } \sup_n \mathbb{E}(\|U_n^0\|^q) < +\infty.$$

- 2) *There exists a deterministic sequence $(M_n)_n$ such that $M_n^2 = o((\gamma_n \log n)^{-1})$ and, for any $n \in \mathbb{N}$,*

$$\forall \theta \in \mathbb{R}^m, \quad \mathbb{E}(\exp(\langle \theta, U_{n+1}^0 \rangle) \mid \mathcal{F}_n) \leq \exp\left(\frac{M_n^2}{2} \|\theta\|^2\right),$$

then (11) is checked.

Proof. For the first point, we refer the reader to Benaïm [4]. Now for the second, let $\theta \in \mathbb{R}^m$ and consider the process $(Z_n(\theta))_n$ defined by

$$Z_n(\theta) := \exp \left(\sum_{i=1}^n \langle \theta, \gamma_i U_i^0 \rangle - \frac{\|\theta\|^2}{2} \sum_{i=1}^n \gamma_i^2 M_i^2 \right).$$

$(Z_n(\theta))_n$ is a supermartingale by assumption. Hence, if we denote $S_n := \sum_{i=n}^{k-1} \gamma_{i+1}^2 M_{i+1}^2$ and $m_n := m(\tau_n + T)$, for any $\beta > 0$,

$$\begin{aligned} \mathbb{P} \left(\sup_{n < k \leq m_n} \left\langle \theta, \sum_{i=n}^{k-1} \gamma_{i+1} U_{i+1} \right\rangle \geq \beta \mid \mathcal{F}_n \right) &= \mathbb{P} \left(\sup_{n < k \leq m_n} \frac{Z_k(\theta)}{Z_n(\theta)} \exp \left(\frac{\|\theta\|^2}{2} \sum_{i=1}^k \gamma_i^2 M_i^2 \right) \geq e^\beta \mid \mathcal{F}_n \right) \\ &\leq \mathbb{P} \left(\sup_{n < k \leq m_n} Z_k(\theta) \geq Z_n(\theta) \exp \left(\beta - \frac{\|\theta\|^2}{2} S_n \right) \mid \mathcal{F}_n \right) \\ &\leq \exp \left(\frac{\|\theta\|^2}{2} S_n - \beta \right). \end{aligned}$$

Let $e \in \{e_1, \dots, e_m, -e_1, \dots, -e_m\}$. We have

$$\begin{aligned} \mathbb{P} \left(\sup_{n < k \leq m_n} \left\langle e, \sum_{i=n}^{k-1} \gamma_{i+1} U_{i+1} \right\rangle \geq \varepsilon \mid \mathcal{F}_n \right) &= \mathbb{P} \left(\sup_{n < k \leq m_n} \left\langle \frac{\delta e}{S_n}, \sum_{i=n}^{k-1} \gamma_{i+1} U_{i+1} \right\rangle \geq \frac{\varepsilon^2}{S_n} \mid \mathcal{F}_n \right) \\ &\leq \exp \left(\frac{-\varepsilon^2}{2S_n} \right). \end{aligned}$$

$$\mathbb{P} \left(\sup_{n < k \leq m_n} \left\| \sum_{i=n}^{k-1} \gamma_{i+1} U_{i+1} \right\| \geq \varepsilon \mid \mathcal{F}_n \right) \leq 2m \exp \left(\frac{-\varepsilon^2}{2S_n} \right).$$

Let us introduce $\varepsilon_n := \gamma_n M_n^2 \log n$. Then, since $\sum_{i=n}^{k-1} \gamma_{i+1} \leq T$, we have

$$\mathbb{P} \left(\sup_{n < k \leq m_n} \left\| \sum_{i=n}^{k-1} \gamma_{i+1} U_{i+1} \right\| \geq \varepsilon \mid \mathcal{F}_n \right) \leq 2m \exp \left(\frac{-\varepsilon^2 \log n}{2T \sup_{k \geq n} \varepsilon_k} \right).$$

Since $\sup_{k \geq n} \varepsilon_k \rightarrow 0$, the application $(n, \varepsilon, T) \mapsto \omega(n, \varepsilon, T) := 2d \sum_{m \geq n} \exp \left(\frac{-\varepsilon^2 \log n}{2T \sup_{k \geq n} \varepsilon_k} \right)$ converges to 0 as n tends to infinity and the proof is complete. ■

Simple examples satisfying the assumptions of Proposition 2.16 are $\gamma_n = 1/n$ and $(U_n^0)_n$ a martingale difference with uniformly bounded moment of order 2 (for 1)) or $\gamma_n = (1/\log(n))^2$ and $(U_n^0)_n$ a uniformly bounded martingale difference (for 2)).

The following is a useful consequence of this statement.

Corollary 2.17. Assume that U_n can be written $U_n = U_n^0 + U_n^1$, where

- $(U_n^0)_n$ a martingale difference noise satisfying one of the assumptions in the Proposition 2.16,
- (11) is satisfied for $(U_n^1)_n$.

Then (11) is satisfied for $(U_n)_n$

Proof. The sum of two random sequences satisfying (11) enjoys the same property. ■

3 Application to the Markovian fictitious play learning model

We discuss here a Markovian strategy in a two-person game and study the induced dynamics. The model is studied by Benaïm and Raimond in [8] and was inspired by a so-called *pairwise comparison dynamics* introduced in Benaïm et al. [7].

3.1 The model

The motivation is the following. We assume, in the initial model, that the *information situation* is the same as in the smooth fictitious play developped by Fudenberg and Levine (see [14] and [15]) where the considered player uses a best response strategy against the empirical moves of his opponent, with respect to a smooth perturbation of the payoff function. A player adopting a smooth fictitious play strategy needs to be informed of his payoff function as well as the moves of his opponents up to this stage.

For some reason (for instance if his set of actions is too large, if he has computational limitations or, more simply, if he is not allowed to play every action at each stage), we consider here that the set of moves he can play at some instant is a subset of his action set, which depends on the last action taken.

More formally, we consider a two players game in normal form. Let I and L be the (finite) sets of moves of respectively player 1 and player 2. These sets are of the form

$$I = \{1, \dots, m^1\}, \quad L = \{1, \dots, m^2\};$$

The maps $(U^1, U^2) : I \times L \rightarrow \mathbb{R} \times \mathbb{R}$ denote the payoff (or utility) functions of players. The sets of mixed strategies available to players are denoted $\mathcal{X} = \Delta(I)$ and $\mathcal{Y} = \Delta(L)$, where

$$\Delta(I) := \left\{ x = (x_1, \dots, x_{m^1}) \in \mathbb{R}_+^{m^1} \mid \sum_{i=1, \dots, m^1} x_i = 1 \right\},$$

and analogously for $\Delta(L)$. The product $\mathcal{X} \times \mathcal{Y}$ is denoted Δ . We will use the classical abuse of language for $y \in \mathcal{Y}$:

$$U^1(i, y) = \sum_{l \in L} U^1(i, l) y_l.$$

For $x \in \mathcal{X}$, $y \in \mathcal{Y}$, we call $br^1(y) := \text{Argmax}_{x \in \mathcal{X}} U^1(x, y)$ and $br^2(x) = \text{Argmax}_{y \in \mathcal{Y}} U^2(x, y)$. We define the set-valued map $F : \mathcal{X} \times \mathcal{Y} \rightrightarrows \mathcal{X} \times \mathcal{Y}$ by

$$F(x, y) = \{(\alpha, \beta) \mid \alpha \in br^1(y) - x, \beta \in br^2(x) - y\}.$$

We assume that a given game is played repeatedly and call X_n (resp. Y_n) the move of player 1 (resp. player 2) at stage n . The empirical distribution of moves up to stage n is denoted \bar{x}_n (resp. \bar{y}_n). We

Let M_0^1 be an irreducible matrix, reversible with respect to its invariant probability distribution π_0^1 , which means that

$$(\pi_0^1)_i M_0^1(i, j) = (\pi_0^1)_j M_0^1(j, i).$$

The matrix M_0^1 represents the possibility or not to play an action depending on the last move: player 1 will be able to play action j after having played i if and only if $M_0^1(i, j) > 0$. For $n \in \mathbb{N}$ and $y \in \mathcal{Y}$, let us define the Markov matrix

$$M_n^1(i, j; y) = \begin{cases} M_0^1(i, j) \exp\left(-\beta_n^1 (U^1(i, y) - U^1(j, y))^+\right) & \text{if } i \neq j, \\ 1 - \sum_{k \neq i} M_n^1(i, k; y) & \text{if } i = j, \end{cases}$$

where $(\beta_n^1)_n$ is some positive deterministic sequence.

Definition 3.1. A Markovian fictitious play (MFP) strategy for player 1, associated with $(\beta_n^1)_n$ and (M_0^1, π_0^1) is a strategy σ such that, for any $n \in \mathbb{N}$,

$$\mathbb{P}_\sigma(X_{n+1} = j \mid \mathcal{F}_n) = M_n^1(X_n, j; \bar{y}_n).$$

From now, we assume that both players use a Markovian fictitious play strategy, associated to M_0^p and $(\beta_n^p)_n$ ($p = 1, 2$). Let us introduce the random sequences

$$V_n := (\delta_{X_n}, \delta_{Y_n}) \quad \text{and} \quad v_n := \frac{1}{n} \sum_{i=1}^n V_i = (\bar{x}_n, \bar{y}_n).$$

We call $Att(v)$ the attainability set of the discrete process $(v_n)_n$. Recall that $p \in Att(v)$ if and only if, for any neighborhood N of p and any $n_0 \in \mathbb{N}$,

$$\mathbb{P}(\exists n \geq n_0 : v_n \in N) > 0.$$

Proposition 3.2. Assume that the matrices M_0^p ($p = 1, 2$) have positive diagonal entries. Then $Att(v)$ is equal to the whole state space Δ .

Proof. By irreducibility, from any instant n , given any player i , any move a_j^i and any positive integer p , player i will play action a_j^i p times in a row with positive probability. ■

Theorem 3.3. Assume that the matrices M_0^p ($p = 1, 2$) have positive diagonal entries. There exist positive values \tilde{A}^p , $p = 1, 2$ (which depend only on the payoff functions and M_0^p , $p = 1, 2$) such that, if agent p plays accordingly to a MFP strategy with $\beta_n^p = A^p \log n$ and $A^p < \tilde{A}^p$, then

$$\mathbb{P}(\mathcal{L}((v_n)_n) \subset A) > 0,$$

for any attractor A for the set-valued dynamical system induced by F .

In particular, a strict Nash equilibrium is always an attractor for the best response dynamics. Hence

Corollary 3.4. Let $\hat{v} = (\hat{x}, \hat{y})$ be a strict Nash equilibrium. Then, under the assumptions of Theorem 3.3,

$$\mathbb{P}(v_n \rightarrow \hat{v}) > 0.$$

Another consequence of Theorem 3.3 is the following. Assume that $U^1 = U^2 = U$ (we will call such a game a *potential game*) and call Λ the set of local maximizers of U :

$$\Lambda = \{u \in \Delta : \exists V_u \in \mathcal{N}_u : \forall v \in V_u, U(v) \leq U(u)\},$$

where \mathcal{N}_u is the set of open neighborhoods of u . The set of Nash equilibria is denoted by NE .

Corollary 3.5. Assume that L is a closed (in Δ) connected component of Λ , which is isolated in the sense that there exists an open neighborhood W of L such that $W \cap \Lambda = L$. Then L is an attractor for the best-response dynamics and therefore, under the assumptions of Theorem 3.3,

$$\mathbb{P}(\mathcal{L}((v_n)_n) \subset L) > 0.$$

Proof. The fact that L is an attractor for the best response dynamics is proved in greater generality in section 3.3, Proposition 3.17. ■

Remark 3.6. Notice that the closedness Λ is essential. Consider a simple example where both players have two actions and the common payoff matrix is

$$A = \begin{pmatrix} 1 & 1 \\ 0 & 2 \end{pmatrix}$$

A direct computation shows that

$$NE = \{((1, 0), (1 - t, t)) : t \in [0, 1/2]\} \cup \{((0, 1), (0, 1))\}.$$

Let us call the first set L_1 and the second L_2 . We easily see that L_2 is an attractor for the best response dynamics. On the other hand, L_1 is a closed connected component of NE but not of Λ since the Nash equilibrium $(x, y) = ((1, 0), (\frac{1}{2}, \frac{1}{2}))$ is not a local maximizer. Thus the connected component $L_1 \setminus \{(x, y)\}$ of Λ is not isolated in NE and Corollary 3.5 can not be applied as it will be made clear in its proof.

3.2 Proof of Theorem 3.3

Notice that the Markov matrix $M_n^1(\cdot, \cdot; y)$ defined in the previous section is reversible with respect to its invariant distribution $\pi_n^1[y]$:

$$(\pi_n^1[y])_i \propto (\pi_0^1)_i \exp(\beta_n U^1(i, y)).$$

Also, considering an irreducible Markovian matrix M and its invariant probability measure π , one can define the pseudo inverse Q of M , characterized by

$$Q(I - M) = (I - M)Q = I - \Pi, \quad Q\mathbf{1} = 0,$$

where Π is the matrix defined by $\Pi(i, j) = \pi(j)$. Let us call π_n^1 and Q_n^1 (respectively π_n^2 and Q_n^2) the invariant probability and the pseudo inverse of the matrix $M_n^1 := M_n^1(\cdot, \cdot; \overline{y}_n)$ (resp. $M_n^2 := M_n^2(\cdot, \cdot; \overline{x}_n)$). We now define the *energy barrier* of M_0^1 with respect to the payoff function U^1 . Let $\Gamma_{i,j}$ be the set of admissible paths from i to j in the graph associated to M_0^1 : $\gamma = (i = i_0, i_1, \dots, i_n = j)$ is admissible if $M_0^1(i_k, i_{k+1}) > 0$, $k = 0, \dots, n-1$. Then, denoting for $y \in \mathcal{Y}$,

$$Elev(i, j; y) := \min \{ \max \{ -U^1(k, y) \mid k \in \gamma \}, \gamma \in \Gamma_{i,j} \}.$$

We call

$$U^{1,\#}(y) := \max \{ Elev(i, j; y) + U^1(i, y) + U^1(j, y) - \max U^1(\cdot, y) \}, \quad U^{1,\#} := \max_{y \in \mathcal{Y}} U^{1,\#}(y).$$

Obviously, the quantity $U^{2,\#}$ is defined analogously.

For $v = (x, y) \in \Delta$, we call $\theta_n(v)$ the random variable

$$\theta_n(v) := (\pi_n^1[y], \pi_n^2[x]).$$

The stochastic process $(v_n)_n$ satisfies the recursive formula

$$v_{n+1} - v_n = \frac{1}{n+1} (-v_n + V_{n+1}) = \frac{1}{n+1} (-v_n + \theta_n(v_n) + U_{n+1}),$$

with

$$U_{n+1} = V_{n+1} - \theta_n = (\delta_{X_{n+1}} - \pi_n^1[\overline{y}_n], \delta_{Y_{n+1}} - \pi_n^2[\overline{x}_n]).$$

Benaïm and Raimond (see Theorem 4.15 in [8]) proved that, if $\beta_n^p = A^p \log n$ with $A^p < \tilde{A}^p := 1/2U^{p,\#}$, then $(v_n)_n$ is a generalised stochastic approximation process, taking values in Δ , with step size $\gamma_n = 1/n$, relatively to the maps $F_n(v) = -v + \theta_n[v]$ and F . Note that the corresponding differential inclusion is the best response dynamics:

$$(\dot{x}, \dot{y}) \in (br^1(y), br^2(x)) - (x, y)$$

However, this is not sufficient to prove Theorem 3.3 and we need to state the stronger property (11) on $(U_n)_n$.

The following proposition can be easily derived from the proof of Proposition 4.4 in Benaïm and Raimond [8].

Proposition 3.7. *Assume that $\beta_n^1 = A^1 \log n$ for some $0 < A^1 < \tilde{A}^1$. Then there exists a positive deterministic sequence $(u_n)_n \rightarrow 0$ such that*

- a) $\frac{|Q_n^1|^2 \log n}{n} \leq u_n$,
- b) $|\Pi_{n+1}^1 - \Pi_n^1| \leq u_n$,
- c) $|Q_{n+1}^1 - Q_n^1| \leq u_n$.

Lemma 3.8. *Assume that the sequences $(\beta_n^p)_n$ ($p = 1, 2$) satisfy the assumption of Proposition 3.7. Then (11) is satisfied for $(1/n)_n$ and $(U_n)_n$.*

Proof. We call ζ_{n+1} the term $\delta_{X_{n+1}} - \pi_n^1[\bar{y}_n]$. We only need to prove that property (11) holds for $1/n$ and $(\zeta_n)_n$. We therefore denote $\Delta(n, T) := \sup_{n < k < m(\tau_n + T)} \left\| \sum_{i=n}^{k-1} \frac{1}{i+1} \zeta_{i+1} \right\|$. First of all, ζ_{n+1} can be written

$$\zeta_{n+1} = \delta_{X_{n+1}} (Id - \Pi_n) = \delta_{X_{n+1}} (Q_n - M_n Q_n).$$

There is then a natural decomposition:

$$\zeta_{n+1} = (\delta_{X_{n+1}} Q_n - \delta_{X_n} M_n Q_n) + (\delta_{X_n} M_n Q_n - \delta_{X_{n+1}} M_n Q_n).$$

The first term is a martingale difference, bounded by $|Q_n|$ (up to a constant). Hence it satisfies the assumption 2) of Proposition 2.16, with $M_n = \sqrt{\frac{nu_n}{\log n}}$.

Now, for the second term, we have

$$\begin{aligned} \sum_{i=n}^{k-1} \frac{1}{i+1} (\delta_{X_i} M_i Q_i - \delta_{X_{i+1}} M_i Q_i) &\leq \sum_{i=n}^{k-1} \frac{1}{i+1} (\delta_{X_{i+1}} M_{i+1} Q_{i+1} - \delta_{X_{i+1}} M_i Q_i) \\ &+ \sum_{i=n}^{k-1} \left(\frac{1}{i} \delta_{X_i} M_i Q_i - \frac{1}{i+1} \delta_{X_{i+1}} M_{i+1} Q_{i+1} \right) + T \sup_{n \leq i \leq k-1} \frac{|Q_i|}{i}, \end{aligned}$$

since $\left\| \sum_{i=n}^k \frac{1}{i(i+1)} \delta_{X_i} M_i Q_i \right\| \leq \sup \{ |Q_i|/i \mid n \leq i \leq k-1 \} \sum_{i=n, \dots, k-1} 1/i$.

The first term on the right side can be written

$$\sum_{i=n}^{k-1} \frac{1}{i+1} \delta_{X_{i+1}} (Q_{i+1} - Q_i + \Pi_{i+1} - \Pi_i),$$

and is bounded by the quantity $T \sup \{|Q_{i+1} - Q_i| + |\Pi_{i+1} - \Pi_i| \mid i = n, \dots, k-1\}$. The telescopic term is bounded by $2 \sup_{n \leq i \leq k-1} \frac{|Q_i|}{i}$. Consequently,

$$\left\| \sum_{i=n}^{k-1} \frac{1}{i+1} (\delta_{X_i} M_i Q_i - \delta_{X_{i+1}} M_i Q_i) \right\| \leq 2(T+1) \sup_{i \geq n} \left\{ \frac{|Q_i|}{i} + |Q_{i+1} - Q_i| + |\Pi_{i+1} - \Pi_i| \right\}.$$

By Proposition 3.7, the term on the right is decreasing to zero and

$$\mathbb{P} \left(\sup_{m \geq n} \Delta(n, T) \geq \varepsilon \mid \mathcal{F}_n \right) \leq \omega(n, \varepsilon, T) \downarrow_n 0.$$

This concludes the proof. ■

3.3 Potential Games and Proof of Corollary 3.5

In this section, we prove that any closed isolated connected component of Λ , the set of local maximizers, is an attractor for the best response dynamics in any given finite N -players potential game. Let $(m^i)_{i=1}^N$ be N natural numbers and assume that the set of pure action for player i is $\{1, \dots, m^i\}$. We call Δ^{m^i} the $m^i - 1$ -dimensional simplex corresponding to its mixed strategies space and U the common n -linear payoff function on $\Delta = \times_{i=1}^N \Delta^{m^i}$ (see section 3.1). We use the notation (x^i, x^{-i}) for $x = (x^1, \dots, x^n) \in \Delta$.

Remark 3.9. *The set Δ can be written as a finite union of the relative interiors $(F_k)_{k=1..K}$ of its faces (this is also true for more general convex sets, see R. Tyrrell Rockafellar [22], Theorem 18.2). Additionally, any F_k is equal to a product $F_k^1 \times \dots \times F_k^N$, where F_k^i is the relative interior of one of Δ^{m^i} 's faces. The restriction of U to F_k can therefore be seen as a smooth function defined on an open set of \mathbb{R}^{n_k} , for some natural number n_k .*

The best response map $BR(x) = (BR^1(x), \dots, BR^n(x))$, where $BR^i(x) = \text{Argmax}_{z \in \Delta^{m^i}} U(z, x^{-i})$, has nonempty compact convex values and is upper semicontinuous. Therefore consider the best response dynamics

$$\dot{x} \in Br(x) - x.$$

Benaïm, Hofbauer and Sorin, in [6], proved that U is a Lyapunov function for NE . Namely, U verifies the following two properties

- (i) $U(x) < U(y)$ for all $x \in \Delta \setminus NE$, $y \in \Phi_t(x)$, $t > 0$,
- (ii) $U(x) \leq U(y)$ for all $x \in NE$, $y \in \Phi_t(x)$, $t \geq 0$.

Lemma 3.10. *Let Λ be the set of local maximizers of U . Then we have*

$$\Lambda \subset NE.$$

Proof. Let x be a local maximizer of U . Since $U(\cdot, x^{-i})$ is linear for all i , we easily derive that x^i is a global maximizer for $U(\cdot, x^{-i})$. ■

Proposition 3.11. *For any finite game Γ , the set of Nash equilibria consists of finitely many connected components.*

For a proof of the above result see Kohlberg and Mertens [17].

Lemma 3.12. *Let $k \in \{1, \dots, K\}$. Then*

$$NE \cap F_k \subset \Sigma_{U|_{F_k}},$$

where $\Sigma_{U|_{F_k}}$ is the set of critical points of $U|_{F_k}$, the restriction of U to F_k .

Proof. Let \tilde{x} be an element of $NE \cap F_k$. By definition of Nash equilibria, we know that, for all $i \in \{1, \dots, N\}$, the point \tilde{x}^i is a global maximizer in F_k^i for the function $U|_{F_k}(\cdot, \tilde{x}^{-i})$. In particular, \tilde{x} is a critical point for $U|_{F_k}$. ■

Lemma 3.13. *The potential function U is constant on every connected component C of NE .*

Proof. Let C be a connected component of NE in Δ . First, we write $C = \cup_{k=1..K} C_k$, where, for any k , $C_k = C \cap F_k$. Pick $k \in \{1, \dots, K\}$. Since $U|_{F_k}$ is smooth, the image of its critical set has null Lebesgue measure by Sard's Lemma. Hence, by Lemma 3.12, this is also true for the image of C_k . In particular, $U(C)$ has null Lebesgue measure, which means that it contains no interval. The result follows by connectedness of C and continuity of U . ■

Remark 3.14. *This result still holds for the more general class of potential games studied in [6], where the strategy spaces are convex compact subsets of euclidean spaces, with countably many faces and the common payoff function is just assumed to be N -concave and smooth. However, Proposition 3.11 is not, a priori, true anymore.*

Lemma 3.15. *Assume that L is a closed (in Δ) isolated connected component of Λ . Then it is also an isolated connected component of NE .*

Proof. By Lemma 3.13, there exists a constant $c \in \mathbb{R}$ such that $U(L) = \{c\}$. Assume that there exists a sequence $(x_n) \subset NE \setminus L$ and $x \in L$ such that (x_n) converges to x . By Proposition 3.11, there exists a connected component of Nash equilibria C which contains L and such that, for n large enough, $x_n \in C$. In particular, $U(x_n) = c$ by Lemma 3.13. Moreover, since x is a local maximizer, there is a neighborhood V of x such that for all $y \in V$, $U(y) \leq c$. For n large enough, $x_n \in V$ and it is also a local maximizer which is a contradiction. Therefore L is isolated in the set of Nash equilibria and $L = C$. ■

The following proposition is a simplified version of Proposition 3.25 in [6].

Proposition 3.16. *Let M be an Euclidean space, $K \subset M$ be a compact set, $V \subset M$ be a bounded open neighborhood of K and $U : \overline{V} \rightarrow \mathbb{R}_-$. Let the following hold :*

- a) *For all $t \geq 0$, $\Phi_t(V) \subset V$ (i.e., V is strongly positively invariant);*
- b) *$U^{-1}(0) = K$;*
- c) *U is continuous and for all $u \in V \setminus K$, $t > 0$ and $v \in \Phi_t(u)$, $U(v) > U(u)$.*

Then there exists an attractor contained in K whose basin contains V , and with $U^{-1}(]-r, 0])$ as a fundamental neighborhood for $r > 0$ small enough.

Proposition 3.17. *If L is a closed (in Δ) isolated connected component of Λ , then it is an attractor for the best response dynamics.*

Proof. By Lemma 3.13, there exists a number $c \in \mathbb{R}$ such that $L \subset U^{-1}(c)$. Without loss of generality we assume that $c = 0$.

In order to use Proposition 3.16, we construct an appropriate open neighborhood V_r of L . First, by Lemma 3.15, there exists an open neighborhood W of L such that

$$W \cap NE = L. \tag{12}$$

Moreover there exists another open neighborhood V of L such that $\bar{V} \subset W$ and, for all $u \in \bar{V} \setminus L$, $U(u) < 0$. Indeed, assume by contradiction that there exists a sequence $(u_n)_n \subset W \setminus L$ which converges to $u \in L$ and such that $U(u_n) \geq 0$ for all $n \geq 0$. There exists a neighborhood V_u of u such that for all $v \in V_u$, $U(v) \leq 0$. For n large enough, V_u is also a neighborhood of u_n , hence $U(u_n) = 0$ and u_n belongs to Λ , which contradicts (12).

By continuity of U , there exists a real number r such that $U^{-1}(]-r, +\infty[) \cap \bar{V} \subset V$. Pick $V_r = U^{-1}(]-r, +\infty[) \cap \bar{V}$ (notice that V_r is an open set, included in V) and consider the function $\tilde{U} : \bar{V}_r \rightarrow \mathbb{R}$ which is the restriction of the function U to \bar{V}_r .

By construction of V_r , we clearly have $\tilde{U}^{-1}(0) = L$ and point b) is therefore checked. Now let $t > 0$, $u \in V_r \setminus L$ and $v \in \Phi_t(u)$. By Property (i) of a Lyapunov function (see p.16), $U(v) > U(u) > -r$ and point c) is satisfied. Now assume that $v \notin V_r$. Then, since $v \in U^{-1}(]-r, +\infty[)$, $v \notin \bar{V}$ and there exists some $0 < t' < t$ and $w \in \Phi_{t'}(u) \cap (\bar{V} \setminus V_r)$, which implies that $U(u) < U(w) \leq -r < U(u)$, a contradiction. Consequently $v \in V_r$. This proves that points a) is checked and Proposition 3.16 applies: there exists an attractor included in L and whose basin of attraction contains V_r . The proposition is proved since L clearly admits no proper attractor. ■

4 Proof of Lemma 2.10

In the following, $L^1([0, T])$ is the set of all Lebesgue-integrable functions from $[0, T]$ to \mathbb{R}^m . Let $H : [0, T] \rightrightarrows \mathbb{R}^m$ be a set-valued map, such that, for any $u \in [0, T]$, $H(u)$ is a nonempty subset of \mathbb{R}^m .

Definition 4.1. We call $\mathcal{S}(H)$ the set of integrable selections from $[0, T]$ to \mathbb{R}^m :

$$\mathcal{S}(H) := \{h \in L^1([0, T]) \text{ such that } \forall u \in [0, T], h(u) \in H(u)\}.$$

With such a definition, we introduce the set-valued integral of H on $[0, T]$:

$$\int_{[0, T]} H(u) du := \left\{ \int_{[0, T]} h(u) du \mid h \in \mathcal{S}(H) \right\}.$$

H is said to be *measurable* if its graph $\{(t, x) \mid x \in H(t)\}$ is measurable and *integrally bounded* if there exists an integrable function $h : [0, T] \rightarrow \mathbb{R}_+$ such that

$$\sup_{x \in H(t)} \|x\| \leq h(t), \quad \forall t \in [0, T].$$

Let $h \in \mathcal{S}(H)$. We call Ψ_h the map defined by $\tau \in [0, T] \mapsto \int_0^\tau h(u) du$.

The following theorem is due to Aumann [2]

Theorem 4.2. Let H be a set-valued map on $[0, T]$ with nonempty images. Then

- * $\int_{[0, T]} H(u) du$ is convex,
- * If H is measurable and integrally bounded then $\int_{[0, T]} H(u) du$ is nonempty.
- * If H has closed images then $\int_{[0, T]} H(u) du$ is compact.
- * If $(H_k)_k$ is a sequence of uniformly integrally bounded set-valued functions then

$$\limsup_k \int_{[0, T]} H_k(u) du \subset \int_{[0, T]} \limsup_k H_k(u) du,$$

where $x \in \limsup_k A_k$ if and only if every neighborhood of x intersects infinitely many A_k .

The next proposition is not a direct consequence of these results. However, the proofs of the third and fourth points can be adapted to derive it:

Proposition 4.3. *Let (H_n) be a sequence of set-valued maps from $[0, T]$ to \mathbb{R}^m uniformly integrally bounded and H be a set-valued map with non empty images. We assume that, for any $\tau \in [0, T]$, $\limsup_n H_n(\tau) \subset H(\tau)$. For any $n \in \mathbb{N}$, let $h_n \in \mathcal{S}(H_n)$. Then,*

- (i) *If, for any u , $H(u)$ is convex, there exists $h \in \mathcal{S}(H)$ such that h_n converges weakly in $L^1([0, T])$ to h (up to a subsequence). In particular, Ψ_{h_n} converges simply to Ψ_h .*
- (ii) *Without the convexity assumption, there exists a function h on $[0, T]$ with the property that, for any $u \in [0, T]$, $h(u) \in \text{co}(H(u))$, the convex hull of $H(u)$ (i.e. the smallest convex set containing A) and such that h_n converges weakly in $L^1([0, T])$ to h . In particular, Ψ_{h_n} converges simply to Ψ_h .*

Proof. Since the sequence (H_n) is uniformly integrally bounded, the h_n are all bounded by an integrable function $g : [0, T] \rightarrow \mathbb{R}_+$. Then there is a subsequence of (h_n) with a weak limit $h \in L^1([0, T])$ (See Dunford and Schwartz [13], Theorem IV.8.9). We may assume without loss of generality that (h_n) actually converges weakly to h . We now prove that h belongs to the set $\mathcal{S}(H)$. For $A \subset L^1([0, T])$, we call $\overline{\text{co}}(A)$ the smallest closed (for the L^1 norm) convex set containing A . Recall that, by Mazur's theorem, a convex subset of $L^1([0, T])$ is closed if and only if it is weakly closed. Consequently, let $k \in \mathbb{N}$. the set $\overline{\text{co}}((h_n)_{n \geq k})$ is closed and convex and therefore weakly closed. Hence it contains h , which belongs to the weakly closed convex hull of $(h_n)_{n \geq k}$. hence,

$$h \in \overline{\text{co}}((h_n)_{n \geq k}) = \overline{\text{co}((h_n)_{n \geq k})},$$

which means that there exists $g_k \in \text{co}((h_n)_{n \geq k})$ such that $\|h - g_k\|_{L^1} \leq 1/k$. Finally, (g_k) converges to h in L^1 and we may assume without loss of generality that $(g_k)_k$ converges to h almost everywhere on $[0, T]$.

From Caratheodory's theorem, the convex hull of a set A is the set of all barycenters of families of $m + 1$ elements of A . Consequently, for any k and $u \in [0, T]$, since $(h_n(u))_{n \geq k}$ is a set of points in \mathbb{R}^m , we have

$$g_k(u) = \sum_{j=0}^m \lambda_k^j(u) e_k^j(u),$$

where $\lambda_k^j(u) \geq 0$, $\sum_{j=0}^m \lambda_k^j(u) = 1$ and $e_k^j(u) \in \{h_n(u) \mid n \geq k\} \subset B(0, g(u))$. By compactness, we may assume that, for any j , $(e_k^j(u))_k$ converges to some $e^j(u)$ and $(\lambda_k^j(u))_k$ converges to $\lambda^j(u)$, such that $\lambda_j(u) \geq 0$ and $\sum_{j=0}^m \lambda^j(u) = 1$. Finally,

$$h(u) = \lim_k g_k(u) = \sum_{j=0}^m \lambda^j(u) e^j(u).$$

For any j , since $e^j(u)$ belongs to the limit set of the sequence $(h_n(u))_n$, it belongs to $H(u)$. Hence, $h(u)$ belongs to $\text{co}(H(u))$ and, if $H(u)$ is convex, $h(u) \in H(u)$. The proof is complete. ■

Lemma 4.4. *Let (K, d) be a compact metric space and $(\Lambda_n)_n, \Lambda : K \rightrightarrows K$ be set-valued maps such that Λ is standard and $\text{Fix}(\Lambda) = \{x \in K \mid x \in \Lambda(x)\} \neq \emptyset$. Assume that, for any $x \in K$,*

$$* \quad \Lambda_{n+1}(x) \subset \Lambda_n(x),$$

$$* \lim_n x_n = x \Rightarrow \limsup_n \Lambda_n(x_n) \subset \Lambda(x).$$

Then, for all $\delta > 0$, there exist $\epsilon > 0$ and $n_0 \in \mathbb{N}$ such that for all $n > n_0$

$$d(x, \Lambda_n(x)) \leq \epsilon \Rightarrow d(x, Fix(\Lambda)) \leq \delta.$$

Proof. First notice that, since $Fix(\Lambda)$ is non empty and $\Lambda_{n+1}(x) \subset \Lambda_n(x)$, there exists $x \in K$ such that $x \in \Lambda_n(x)$ for all n . Assume that there are $\delta > 0$, a strictly increasing sequence of integers $(n_k)_{k \geq 1}$ and a sequence $(x_k)_{k \geq 1}$ in K such that

$$d(x_k, \Lambda_{n_k}(x_k)) \leq \frac{1}{k} \text{ and } d(x_k, Fix(\Lambda)) > \delta.$$

Then, there exists a sequence $(y_k)_{k \geq 1}$ such that $y_k \in \Lambda_{n_k}(x_k)$ and

$$d(x_k, y_k) \leq \frac{1}{k} \text{ and } d(x_k, Fix(\Lambda)) > \delta.$$

Without loss of generality, we may assume that $x_k \rightarrow x \in K$ and $y_k \rightarrow y$. Consequently, $d(x, Fix(\Lambda)) \geq \delta > 0$ and $x = y$. On the other hand,

$$y \in \limsup_k \Lambda_{n_k}(x_k) \subset \limsup_k \Lambda_k(x_k) \subset \Lambda(x),$$

which means that $x \in \Lambda(x)$, a contradiction. ■

Remark 4.5. If the Λ_n are closed, then it is sufficient to assume that $\cap_n \Lambda_n(x) = \Lambda(x)$, $\forall x$. Indeed, by monotonicity and the fact that Λ_{n_k} is closed, $y \in \Lambda_{n_k}(x)$, $\forall k$.

From now, we consider a bounded standard set-valued map $F : \mathbb{R}^m \rightrightarrows \mathbb{R}^m$ and $T > 0$. Let δ be a positive real number. Then F^δ is the set-valued map defined by (6) and Λ^δ is the set-valued map defined by (9), extended to $\mathcal{C}([0, T], \mathbb{R}^m)$. Note that, with our current notations, the definition of the set-valued map Λ^δ can be written, for $\delta \geq 0$:

$$\Lambda^\delta : \mathcal{C}([0, T], \mathbb{R}^m) \rightrightarrows \mathcal{C}([0, T], \mathbb{R}^m), \quad \mathbf{z} \mapsto \{\mathbf{z}(0) + \Psi_h \mid h \in \mathcal{S}(F^\delta(\mathbf{z}))\}.$$

Proposition 4.6. Λ is a closed set-valued map with non empty images.

Proof. First, Λ has non empty images since $\int_0^T F(\mathbf{z})$ is non empty, for any \mathbf{z} (see Theorem 4.2). Let $(\mathbf{z}_n)_n$ be a sequence of $\mathcal{C}([0, T], \mathbb{R}^m)$, which converges to some \mathbf{z} in $\mathcal{C}([0, T], \mathbb{R}^m)$ and let $(\mathbf{y}_n)_n$ be a sequence converging to \mathbf{y} such that, for all $n \in \mathbb{N}$, $\mathbf{y}_n \in \Lambda(\mathbf{z}_n)$. This implies that,

$$\forall n \in \mathbb{N}, \exists h_n \in \mathcal{S}(F(\mathbf{z}_n)) \text{ such that } \mathbf{y}_n(\tau) = \mathbf{z}_n(0) + \Psi_{h_n}(\tau).$$

We call $H_n := F(\mathbf{z}_n)$ and $H := F(\mathbf{z})$. By assumptions we made on F , H_n and H have compact, convex and nonempty values. For $\tau \in [0, T]$, $\mathbf{z}_n(\tau)$ converges to $\mathbf{z}(\tau)$ and, since the graph of F is closed,

$$\limsup_n H_n(\tau) = \limsup_n F(\mathbf{z}_n(\tau)) \subset F(\mathbf{z}(\tau)) = H(\tau).$$

The assumptions of Proposition 4.3 are satisfied. Hence, there exists $h \in \mathcal{S}(F(\mathbf{z}))$ such that $\mathbf{y} = \mathbf{z}(0) + \Psi_h$. ■

Lemma 4.7. For any $\delta > 0$, F^δ is a closed set-valued map with non empty images.

Proof. Let $x \in \mathbb{R}^m$. $F(x)$ is contained in F^δ . Hence, it is not empty. Let $x_n \rightarrow x$ and $(y_n)_n$ be a sequence of $F^\delta(x_n)$ converging to some y . Then there exists a sequence $(z_n)_n$ such that

$$d(z_n, x_n) < \delta \text{ and } d(y_n, F(z_n)) < \delta.$$

hence there exists a sequence $(\alpha_n)_n$ such that $\alpha_n \in F(z_n)$ and $d(y_n, \alpha_n) < \delta$. Without loss of generality, we may assume that $z_n \rightarrow z$ and $\alpha_n \rightarrow \alpha$. By closeness of the graph of F , we obtain

$$d(z, x) < \delta, \alpha \in F(z) \text{ and } d(y, \alpha) < \delta,$$

and F^δ is closed (and, in particular, has closed images). ■

Remark 4.8. Note that the images are, a priori, not convex.

Lemma 4.9. Let $(x_n)_n$ be a sequence of \mathbb{R}^m , converging to x and $(\delta_n)_n$ be a positive, vanishing sequence. Then we have

$$\limsup_{n \rightarrow +\infty} F^{\delta_n}(x_n) \subset F(x).$$

Proof. Let $y \in \limsup_n F^{\delta_n}(x_n)$. By definition, there exists a sequence (y_n) which converges to y and such that $y_n \in F^{\delta_n}(x_n)$ (actually it is a subsequence but there is no loss of generality to keep the initial indexation). Hence there exists a sequence (z_n) such that

$$d(z_n, x_n) < \delta_n, \quad d(y_n, F(z_n)) < \delta_n,$$

which means that $d(x_n, \alpha_n) < \delta_n$ for some sequence $(\alpha_n)_n$ satisfying $\alpha_n \in F(z_n)$. Without loss of generality we may assume that $\alpha_n \rightarrow \alpha$ and $z_n \rightarrow z$. Hence we have $y = \alpha \in F(z) = F(x)$. ■

Corollary 4.10. Let $(\mathbf{z}_n)_n$ be a sequence converging to \mathbf{z} in $\mathcal{C}([0, T], \mathbb{R}^m)$. Then we have, for any positive, vanishing sequence $(\delta_n)_n$,

$$\limsup_{n \rightarrow +\infty} \Lambda^{\delta_n}(\mathbf{z}_n) \subset \Lambda(\mathbf{z}).$$

Proof. Let $\mathbf{y} \in \limsup_n \Lambda^{\delta_n}(\mathbf{z}_n)$. This means that there exists a sequence $\mathbf{y}_n \in \Lambda^{\delta_n}(\mathbf{z}_n)$ which converges to \mathbf{y} . Hence, for all $n \in \mathbb{N}$, there exists $h_n \in \mathcal{S}(F^{\delta_n}(\mathbf{z}_n))$ such that

$$\forall \tau \in [0, T], \quad \mathbf{y}_n(\tau) = \mathbf{z}_n(0) + \int_0^\tau h_n(u) du$$

By Corollary 4.3 and Lemma 4.9, there exists a function h on $[0, T]$ such that

$$\int_0^\tau h_n(u) du \rightarrow_n \int_0^\tau h(u) du, \quad \forall \tau \in [0, T]$$

and $h \in \mathcal{S}(F(\mathbf{z}))$, which completes the proof. ■

Corollary 4.11. Let $\Lambda_n := \Lambda^{\delta_n}$. Suppose there exists a compact $K \subset \mathcal{C}([0, T], \mathbb{R}^m)$ such that $\Lambda_n : K \rightrightarrows K$ for all n . Then, for all $\delta > 0$, there exists $\epsilon > 0$ and $n_0 \in \mathbb{N}$ such that, for all $n > n_0$,

$$d(\mathbf{z}, \Lambda_n(\mathbf{z})) \leq \epsilon \Rightarrow d(\mathbf{z}, \text{Fix}(\Lambda)) \leq \delta.$$

Proof. This result follows from Lemma 4.4 and Corollary 4.10. ■

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