A Generalization of the Borkar-Meyn Theorem for Stochastic Recursive Inclusions

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Abstract

In this paper the stability theorem of **Borkar and Meyn** is extended to include the case when the mean field is a set-valued map. Two different sets of sufficient conditions are presented that guarantee the 'stability and convergence' of stochastic recursive inclusions. Our work builds on the works of **Benaïm**, **Hofbauer and Sorin** as well as **Borkar and Meyn**. As a corollary to one of the main theorems, a natural generalization of the *Borkar and Meyn Theorem* follows. In addition, the original theorem of *Borkar and Meyn* is shown to hold under slightly relaxed assumptions. As an application to one of the main theorems we discuss a solution to the 'approximate drift problem'. Finally, we analyze the stochastic gradient algorithm with "constant error gradient estimators" as yet another application of our main result.

1 Introduction

Consider the following recursion in \mathbb{R}^d $(d \geq 1)$:

$$x_{n+1} = x_n + a(n) [h(x_n) + M_{n+1}], \text{ for } n \ge 0, \text{ where}$$
 (1)

- (i) $h: \mathbb{R}^d \to \mathbb{R}^d$ is a Lipschitz continuous function.
- (ii) a(n) > 0, for all n, is the step-size sequence satisfying $\sum_{n=0}^{\infty} a(n) = \infty$ and $\sum_{n=0}^{\infty} a(n)^2 < \infty$.
- (iii) M_n , $n \ge 1$, is a sequence of martingale difference terms that constitute the noise.

The stochastic recursion given by (1) is often referred to as a *stochastic* recursive equation (SRE). A powerful method to analyze the limiting behavior of (1) is the ODE (Ordinary Differential Equation) method. Here the limiting

behavior of the algorithm is described in terms of the asymptotics of the solution to the \it{ODE}

$$\dot{x}(t) = h(x(t)).$$

This method was introduced by **Ljung** [12] in 1977. For a detailed exposition on the subject and a survey of results, the reader is referred to **Kushner and Yin** [11] as well as **Borkar** [10].

In 1996, **Benaïm** [4] showed that the asymptotic behavior of a stochastic recursive equation can be studied by analyzing the asymptotic behavior of the associated o.d.e. However no assumptions were made on the dynamics of the o.d.e. Specifically, he developed sufficient conditions which guarantee that limit sets of the continuously interpolated stochastic iterates are compact, connected, internally chain transitive and invariant sets of the associated o.d.e. The results found in [4] are generalized in [5]; further studies were made by Benaïm and **Hirsch** in [6]. The assumptions made in [4] are sometimes referred to as the 'classical assumptions'. One of the key assumptions used by Benaïm to prove this convergence theorem is the almost sure boundedness of the iterates i.e., stability of the iterates. In 1999, Borkar and Meyn [13] developed sufficient conditions which guarantee both the stability and convergence of stochastic recursive equations. These assumptions were consistent with those developed in [4]. In this paper we refer to the main result of **Borkar and Meyn** colloquially as the Borkar-Meyn Theorem. In the same paper [13], several applications to problems from reinforcement learning have also been discussed. Another set of sufficient conditions for SRE's were developed by Andrieu, Moulines and **Priouret** [1] using global Lyapunov functions that guarantee the stability and convergence of the iterates.

In 2005, **Benaïm**, **Hofbauer and Sorin** [7] showed that the dynamical systems approach can be extended to the situation where the mean fields are *set-valued*. The algorithms considered were of the form:

$$x_{n+1} = x_n + a(n)[y_n + M_{n+1}], \text{ for } n \ge 0, \text{ where}$$
 (2)

- (i) $y_n \in h(x_n)$ and $h : \mathbb{R}^d \to \{subsets \ of \ \mathbb{R}^d\}$ is a Marchaud map. For the definition of Marchaud maps the reader is referred to section 2.1.
- (ii) a(n)>0, for all $n\geq 0$, is the step-size sequence satisfying $\sum_{n=0}^{\infty}a(n)=\infty$ and $\sum_{n=0}^{\infty}a(n)^2<\infty$.
- (iii) M_n , $n \ge 1$, is a sequence of martingale difference terms.

A recursion such as (2) is also called *stochastic recursive inclusion (SRI)*. Since a differential equation can be seen as a special case of a differential inclusion wherein h(x) is a cardinality one set for all $x \in \mathbb{R}^d$, SRE (1) can be seen as a special case of SRI (2).

The main aim of this paper is to extend the original *Borkar-Meyn theorem* to the case of stochastic recursive inclusions. We present two overlapping yet different sets of assumptions, in Sections 2.2 and 3.3 respectively, that guarantee the stability and convergence of a *SRI* given by (2). As a consequence of our

main results, Theorems 2 and 3, we present a couple of interesting extensions to the original theorem of Borkar and Meyn in Section 4. Using the frameworks presented herein we provide a solution to the problem of approximate drift in Section 5.1. For more details on the approximate drift problem the reader is referred to Borkar [10]. In Section 6 we discuss the generality, ease of verifiability and we also try to explain why the assumptions are "natural" in some sense.

Stochastic gradient descent (SGD) is an important method to find minima of (continuously) differentiable functions. When implementing the corresponding approximation algorithm (See (13) in Section 5.2) using gradient estimators, an error is made at each step in calculating the gradient of the objective function. Lets call this error the "approximation error". This is the case when using gradient estimators such as Kiefer-Wolfowitz, simultaneous perturbation stochastic approximation (SPSA) and smoothed functional (SF) schemes, see [9]. Suppose the perturbation parameters of the aforementioned estimators are kept constant, then the "approximation error" is bounded by a constant that depends on the size of the perturbation parameters. We call such estimators constant-error gradient estimators. In Section 5.2 we analyze the stochastic gradient approximation algorithm that uses a constant-error gradient estimator. Using Theorem 3 we show that the iterates are stable and converge to a δ -neighborhood of the minimum set, for a specified $\delta(>0)$. Essentially, our framework gives a threshold $\epsilon(\delta)$ for the "approximation error" so that the stochastic gradient approximation algorithm is stable and converges to a δ -neighborhood of the minimum set.

It is worth noting that prior to this paper one could only claim that an SGD using constant-error gradient estimators will only converge to some neighborhood of the minimum set with high probability. On the other hand, our framework guarantees almost sure convergence to a small neighborhood of the minimum set.

2 Preliminaries and Assumptions

2.1 Definitions and Notations

The definitions and notations used in this paper are similar to those in Benaïm et. al. [7], Aubin et. al. [2], [3] and Borkar [10]. In this section, we present a few for easy reference.

A set-valued map $h: \mathbb{R}^n \to \{subsets\ of\ \mathbb{R}^m\ \}$ is called a Marchaud map if it satisfies the following properties:

- (i) For each $x \in \mathbb{R}^n$, h(x) is convex and compact.
- (ii) (point-wise boundedness) For each $x \in \mathbb{R}^n$, $\sup_{w \in h(x)} \|w\| < K(1 + \|x\|)$ for some K > 0.
- (iii) h is an upper-semicontinuous map. We say that h is upper-semicontinuous, if given sequences $\{x_n\}_{n\geq 1}$ (in \mathbb{R}^n) and $\{y_n\}_{n\geq 1}$ (in \mathbb{R}^m) with $x_n\to x$,

 $y_n \to y$ and $y_n \in h(x_n), n \ge 1$, implies that $y \in h(x)$. In other words the graph of h, $\{(x,y): y \in h(x), x \in \mathbb{R}^n\}$, is closed in $\mathbb{R}^n \times \mathbb{R}^m$.

Let H be a Marchaud map on \mathbb{R}^d . The differential inclusion (DI) given by

$$\dot{x} \in H(x) \tag{3}$$

is guaranteed to have at least one solution that is absolutely continuous. The reader is referred to [2] for more details. We say that $\mathbf{x} \in \sum$ if \mathbf{x} is an absolutely continuous map that satisfies (3). The set-valued semiflow Φ associated with (3) is defined on $[0, +\infty) \times \mathbb{R}^d$ as:

 $\Phi_t(x) = \{\mathbf{x}(t) \mid \mathbf{x} \in \sum, \mathbf{x}(0) = x\}.$ Let $B \times M \subset [0, +\infty) \times \mathbb{R}^k$ and define

$$\Phi_B(M) = \bigcup_{t \in B, \ x \in M} \Phi_t(x).$$

Let $M \subseteq \mathbb{R}^d$, the ω – limit set be defined by $\omega_{\Phi}(M) = \bigcap_{t>0} \overline{\Phi_{[t,+\infty)}(M)}$. Similarly the *limit set* of a solution **x** is given by $L(x) = \bigcap_{t>0} \overline{\mathbf{x}([t,+\infty))}$.

 $M \subseteq \mathbb{R}^d$ is invariant if for every $x \in M$ there exists a trajectory, \mathbf{x} , entirely

in M with $\mathbf{x}(0) = x$. In other words, $\mathbf{x} \in \sum$ with $\mathbf{x}(t) \in M$, for all $t \geq 0$. Let $x \in \mathbb{R}^d$ and $A \subseteq \mathbb{R}^d$, then $d(x,A) := \inf\{\|a - y\| \mid y \in A\}$. We define the δ -open neighborhood of A by $N^{\delta}(A) := \{x \mid d(x,A) < \delta\}$. The δ -closed neighborhood of A is defined by $\overline{N^{\delta}}(A) := \{x \mid d(x,A) \leq \delta\}$. The open ball of radius r around the origin is represented by $B_r(0)$, while the closed ball is represented by $\overline{B}_r(0)$.

Internally Chain Transitive Set: $M \subset \mathbb{R}^d$ is said to be internally chain transitive if M is compact and for every $x, y \in M$, $\epsilon > 0$ and T > 0 we have the following: There exist Φ^1, \ldots, Φ^n that are n solutions to the differential inclusion $\dot{x}(t) \in h(x(t))$, a sequence $x_1(=x), \ldots, x_{n+1}(=y) \subset M$ and n real numbers t_1, t_2, \ldots, t_n greater than T such that: $\Phi^i_{t_i}(x_i) \in N^{\epsilon}(x_{i+1})$ and $\Phi^i_{[0,t_i]}(x_i) \subset M$ for $1 \leq i \leq n$. The sequence $(x_1(=x), \ldots, x_{n+1}(=y))$ is called an (ϵ, T) chain in M from x to y.

 $A \subseteq \mathbb{R}^d$ is an attracting set if it is compact and there exists a neighborhood U such that for any $\epsilon > 0$, $\exists T(\epsilon) \geq 0$ with $\Phi_{T(\epsilon),+\infty}(U) \subset N^{\epsilon}(A)$. Such a U is called the fundamental neighborhood of A. In addition to being compact if the attracting set is also invariant then it is called an attractor. The basin of attraction of A is given by $B(A) = \{x \mid \omega_{\Phi}(x) \subset A\}$. It is called Lyapunov stable if for all $\delta > 0$, $\exists \epsilon > 0$ such that $\Phi_{[0,+\infty)}(N^{\epsilon}(A)) \subseteq N^{\delta}(A)$. We use $T(\epsilon)$ and T_{ϵ} interchangeably to denote the dependence of T on ϵ .

We define the lower and upper limits of sequences of sets. Let $\{K_n\}_{n\geq 1}$ be a sequence of sets in \mathbb{R}^d .

- 1. The lower limit of $\{K_n\}_{n\geq 1}$ is given by, $Liminf_{n\to\infty}K_n:=\{x\mid \lim_{n\to\infty}d(x,K_n)=1\}$
- 2. The upper-limit of $\{K_n\}_{n\geq 1}$ is given by, $Limsup_{n\to\infty}K_n:=\{y\mid \underset{n\to\infty}{\underline{lim}}d(y,K_n)=1\}$

We may interpret that the lower-limit collects the limit points of $\{K_n\}_{n\geq 1}$ while the upper-limit collects its accumulation points.

2.2 The assumptions

Recall that we have the following recursion in \mathbb{R}^d :

$$x_{n+1} = x_n + a(n) [y_n + M_{n+1}], \text{ where } y_n \in h(x_n).$$

We state our assumptions below:

- (A1) $h: \mathbb{R}^d \to \{\text{subsets of } \mathbb{R}^d\}$ is a Marchaud map.
- (A2) $\{a(n)\}_{n\geq 0}$ is a scalar sequence such that: $a(n)>0 \ \forall n, \ \sum_{n\geq 0} a(n)=\infty$ and $\sum_{n\geq 0} a(n)^2 < \infty$. Without loss of generality we let $\sup_n a(n) \leq 1$.
- (A3) $\{M_n\}_{n\geq 1}$ is a martingale difference sequence with respect to the filtration $\mathcal{F}_n := \sigma(x_0, M_1, \dots, M_n), n \geq 0.$
 - (i) $\{M_n\}_{n>1}$ is a square integrable sequence.
 - (ii) $E[\|M_{n+1}\|^2|\mathcal{F}_n] \leq K(1+\|x_n\|^2)$, for $n \geq 0$ and some constant K > 0. Without loss of generality assume that the same constant, K, works for both the point-wise boundedness condition of (A1) (see condition (ii) in the definition of Marchaud map in Section 2.1) and (A3).

For $c \geq 1$ and $x \in \mathbb{R}^d$, define $h_c(x) = \{y \mid cy \in h(cx)\}$. Further, for each $x \in \mathbb{R}^d$, define $h_{\infty}(x) := \overline{Liminf_{c \to \infty} h_c(x)}$ i.e. the closure of the lower-limit of $\{h_c(x)\}_{c \geq 1}$.

- (A4) $h_{\infty}(x)$ is non-empty for all $x \in \mathbb{R}^d$. Further, the differential inclusion $\dot{x}(t) \in h_{\infty}(x(t))$ has an attracting set, \mathcal{A} , with $\overline{B}_1(0)$ as a subset of its fundamental neighborhood. This attracting set is such that $\mathcal{A} \subseteq B_1(0)$.
- **(A5)** Let $c_n \geq 1$ be an increasing sequence of integers such that $c_n \uparrow \infty$ as $n \to \infty$. Further, let $x_n \to x$ and $y_n \to y$ as $n \to \infty$, such that $y_n \in h_{c_n}(x_n), \forall n$, then $y \in h_{\infty}(x)$.

Since the attracting set, $A \subseteq B_1(0)$, is compact we conclude that $\sup_{x \in A} \|x\| < 1$. To see this, for all $x \in A$ define $\delta(x) := \sup_{y \in \overline{B}_{\epsilon(x)}(x)} \|y\|$, where $\epsilon(x) > 0$ and $\overline{B}_{\epsilon(x)}(x) \subseteq B_1(0)$. For all $x \in A$ we have $\delta(x) < 1$. Further, $\{B_{\epsilon(x)}(x) \mid x \in A\}$ is an open cover of A. Let $\{B_{\epsilon(x_i)}(x_i) \mid 1 \le i \le n\}$ be a finite sub-cover and $\delta := \max_{1 \le i \le n} \delta(x_i)$. Clearly, it follows that $\sup_{x \in A} \|x\| \le \delta < 1$. Define $\delta_1 := \sup_{x \in A} \|x\|$ and pick real numbers δ_2 , δ_3 and δ_4 such that $\sup_{x \in A} \|x\| = \delta_1 < \delta_2 < \delta_3 < \delta_4 < 1$. We shall use this sequence later on.

Assumptions (A1) - (A3) are the same as in Benaim [7]. However, the assumption on the stability of the iterates is replaced by (A4) and (A5). We show that (A4) and (A5) are sufficient conditions to ensure stability of iterates. We start by observing that h_c and h_{∞} are Marchaud maps, where $c \geq 1$. Further, we show that the constant associated with the point-wise boundedness property is K of (A1) and (A3).

Proposition 1. h_{∞} and h_c , $c \geq 1$, are Marchaud maps.

Proof. Fix $c \geq 1$ and $x \in \mathbb{R}^d$. To prove that $h_c(x)$ is compact, we show that it is closed and bounded. For $n \geq 1$, let $y_n \in h_c(x)$ and let $\lim_{n \to \infty} y_n = y$. It follows that $cy_n \in h(cx)$ for each $n \geq 1$ and $\lim_{n \to \infty} cy_n = cy$. Since h(cx) is closed, we have that $cy \in h(cx)$ and $y \in h_c(x)$. If we show that h_c is point-wise bounded then we can conclude that $h_c(x)$ is compact. To prove the aforementioned, let $y \in h_c(x)$, then $cy \in h(cx)$. Since h satisfies (A1)(ii), we have that

$$c||y|| \le K(1 + ||cx||)$$
, hence

$$||y|| \le K\left(\frac{1}{c} + ||x||\right).$$

Since $c(\geq 1)$ and x is arbitrarily chosen, h_c is point-wise bounded and the compactness of $h_c(x)$ follows. The set $h_c(x) = \{z/c \mid z \in h(cx)\}$ is convex since h(cx) is convex and $h_c(x)$ is obtained by scaling it by $\frac{1}{c}$.

Next, we show that $h_c(x)$ is upper-semicontinuous. Let $\lim_{n\to\infty} x_n = x$, $\lim_{n\to\infty} y_n = y$ and $y_n \in h_c(x_n)$, $\forall n \geq 1$. We need to show that $y \in h_c(x)$. We have that $cy_n \in h(cx_n)$ for each $n \geq 1$. Since $\lim_{n\to\infty} cx_n = cx$ and $\lim_{n\to\infty} cy_n = cy$, we conclude that $cy \in h(cx)$ since h is assumed to be upper-semicontinuous.

It is left to show that $h_{\infty}(x)$, $x \in \mathbb{R}^d$ is a Marchaud map. To prove that $||z|| \le K (1 + ||x||)$ for all $z \in h_{\infty}(x)$, it is enough to prove that $||y|| \le K (1 + ||x||)$ for all $y \in Liminf_{c \to \infty} h_c(x)$. Fix some $y \in Liminf_{c \to \infty} h_c(x)$ then there exist $z_n \in h_n(x)$, $n \ge 1$, such that $\lim_{n \to \infty} ||y - z_n|| = 0$. We have that

$$||y|| \le ||y - z_n|| + ||z_n||.$$

Since h_c , $c \ge 1$, is point-wise bounded (the constant associated is independent of c and equals K), the above inequality becomes

$$||y|| \le ||y - z_n|| + K(1 + ||x||).$$

Letting $n \to \infty$ in the above inequality, we obtain $||y|| \le K(1 + ||x||)$. Recall that $h_{\infty}(x) = \overline{Liminf_{c\to\infty} h_{c}(x)}$, hence it is compact.

Again, to show that $h_{\infty}(x)$ is convex, for each $x \in \mathbb{R}^d$, we start by proving that $Liminf_{c\to\infty} h_c(x)$ is convex. Let $u,v \in Liminf_{c\to\infty} h_c(x)$ and $0 \le t \le 1$. We need to show that $tu + (1-t)v \in Liminf_{c\to\infty} h_c(x)$. Consider an arbitrary sequence $\{c_n\}_{n\ge 1}$ such that $c_n\to\infty$, then there exist $u_n,v_n\in h_{c_n}(x)$ such that

 $||u_n - u||$ and $||v_n - v|| \to 0$ as $c_n \to \infty$. Since $h_{c_n}(x)$ is convex, it follows that $tu_n + (1-t)v_n \in h_{c_n}(x)$, further

$$\lim_{c_n \to \infty} (tu_n + (1-t)v_n) = tu + (1-t)v.$$

Since we started with an arbitrary sequence $c_n \to \infty$, it follows that $tu + (1-t)v \in Liminf_{c\to\infty} h_c(x)$. Now we can prove that $h_{\infty}(x)$ is convex. Let $u, v \in h_{\infty}(x)$. Then $\exists \{u_n\}_{n\geq 1}$ and $\{v_n\}_{n\geq 1} \subseteq Liminf_{c\to\infty} h_c(x)$ such that $u_n \to u$ and $v_n \to v$ as $n \to \infty$. We need to show that $tu + (1-t)v \in h_{\infty}(x)$, for $0 \le t \le 1$. Since $tu_n + (1-t)v_n \in Liminf_{c\to\infty} h_c(x)$, the desired result is obtained by letting $n \to \infty$ in $tu_n + (1-t)v_n$.

Finally, we show that h_{∞} is upper-semicontinuous. Let $\lim_{n\to\infty} x_n = x$, $\lim_{n\to\infty} y_n = y$ and $y_n \in h_{\infty}(x_n)$, $\forall n \geq 1$. We need to show that $y \in h_{\infty}(x)$. Since $y_n \in h_{\infty}(x_n)$, $\exists z_n \in Liminf_{c\to\infty} h_c(x_n)$ such that $||z_n - y_n|| < \frac{1}{n}$. Since $z_n \in Liminf_{c\to\infty} h_c(x_n)$, $n \geq 1$, it follows that there exist c_n such that for all $c \geq c_n$, $d(z_n, h_c(x_n)) < \frac{1}{n}$. In particular, $\exists u_n \in h_{c_n}(x_n)$ such that $||z_n - u_n|| < \frac{1}{n}$. We choose the sequence $\{c_n\}_{n\geq 1}$ such that $c_{n+1} > c_n$ for each $n \geq 1$. We now have the following: $\lim_{n\to\infty} u_n = y$, $u_n \in h_{c_n}(x_n) \ \forall n$ and $\lim_{n\to\infty} x_n = x$. It follows directly from assumption (A5) that $y \in h_{\infty}(x)$.

3 Stability and convergence of stochastic recursive inclusions

We begin by providing a brief outline of our approach to prove the stability of a SRI under assumptions (A1)-(A5). First we divide the time line, $[0,\infty)$, approximately into intervals of length T. We shall explain later how we choose and fix T. Then we construct a linearly interpolated trajectory from the given stochastic recursive inclusion; the construction is explained in the next paragraph. A sequence of 'rescaled' trajectories of length T is constructed as follows: At the beginning of each T-length interval we observe the trajectory to see if it is outside the unit ball, if so we scale it back to the boundary of the unit ball. This scaling factor is then used to scale the 'rest of the T-length trajectory'.

To show that the iterates are bounded almost surely we need to show that the linearly interpolated trajectory does not 'run off' to infinity. To do so we assume that this is not true and show that there exists a subsequence of the rescaled T-length trajectories that has a solution to $\dot{x}(t) \in h_{\infty}(x(t))$ as a limit point in $C([0,T],\mathbb{R}^d)$. We choose and fix T such that any solution to $\dot{x}(t) \in h_{\infty}(x(t))$ with an initial value inside the unit ball is close to the origin at the end of time T. In this paper we choose $T = T(\delta_2 - \delta_1) + 1$. We then argue that the linearly interpolated trajectory is forced to make arbitrarily large 'jumps' within time T. The Gronwall inequality is then used to show that this is not possible.

Once we prove stability of the recursion we invoke *Theorem 3.6 & Lemma 3.8* from **Benaïm**, **Hofbauer and Sorin** [7] to conclude that the limit set is a closed, connected, internally chain transitive and invariant set associated with $\dot{x}(t) \in h_{\infty}(x(t))$.

We construct the linearly interpolated trajectory $\overline{x}(t)$, for $t \in [0, \infty)$, from the sequence $\{x_n\}$ as follows: Define t(0) := 0, $t(n) := \sum_{i=0}^{n-1} a(i)$. Let $\overline{x}(t(n)) := x_n$ and for $t \in (t(n), t(n+1))$, let

$$\overline{x}(t) \ := \ \left(\frac{t(n+1)-t}{t(n+1)-t(n)}\right) \ \overline{x}(t(n)) \ + \ \left(\frac{t-t(n)}{t(n+1)-t(n)}\right) \ \overline{x}(t(n+1)).$$

We define a piecewise constant trajectory using the sequence $\{y_n\}_{n\geq 0}$ as follows: $\overline{y(t)} := y_n$ for $t \in [t(n), t(n+1)), n \geq 0$.

We know that the DI given by $\dot{x}(t) \in h_{\infty}(x(t))$ has an attractor set \mathcal{A} such that $\delta_1 := \sup_{x \in \mathcal{A}} ||x|| < 1$. Let us fix $T := T(\delta_2 - \delta_1) + 1$, where $T(\delta_2 - \delta_1)$ is as defined in section 2.1. Then, $||x(t)|| < \delta_2$, for all $t \geq T(\delta_2 - \delta_1)$, where $\{x(t) : t \in [0, \infty)\}$ is a solution to $\dot{x}(t) \in h_{\infty}(x(t))$ with an initial value inside the unit ball around the origin.

Define $T_0 := 0$ and $T_n := \min\{t(m) : t(m) \ge T_{n-1} + T\}, n \ge 1$. Observe that there exists a subsequence $\{m(n)\}_{n\ge 0}$ of $\{n\}$ such that $T_n = t(m(n))$ $\forall n \ge 0$. We construct the rescaled trajectory, $\hat{x}(t), t \ge 0$, as follows: Let $t \in [T_n, T_{n+1})$ for some $n \ge 0$, then $\hat{x}(t) := \frac{\overline{x}(t)}{r(n)}$, where $r(n) = \|\overline{x}(T_n)\| \lor 1$. Also, let $\hat{x}(T_{n+1}^-) := \lim_{t \uparrow T_{n+1}} \hat{x}(t), t \in [T_n, T_{n+1})$. The corresponding 'rescaled y

iterates' are given by $\hat{y}(t) := \frac{\overline{y(t)}}{r(n)}$ and the rescaled martingale noise terms by $\hat{M}_{k+1} := \frac{M_{k+1}}{r(n)}, t(k) \in [T_n, T_{n+1}), n \geq 0.$

Consider the recursion at hand, i.e.,

$$\overline{x}(t(k+1)) = \overline{x}(t(k)) + a(k)(\overline{y}(t(k)) + M_{k+1}),$$

such that t(k), $t(k+1) \in [T_n, T_{n+1})$. Multiplying both sides by 1/r(n) we get the rescaled recursion:

$$\hat{x}(t(k+1)) \ = \ \hat{x}(t(k)) \ + \ a(k) \left(\hat{y}(t(k)) \ + \ \hat{M}_{k+1} \right).$$

Since $\overline{y}(t(k)) \in h\left(\overline{x}(t(k))\right)$, it follows that $\hat{y}(t(k)) \in h_{r(n)}\left(\hat{x}(t(k))\right)$. It is worth noting that $E\left[\|\hat{M}_{k+1}\|^2|\mathcal{F}_k\right] \leq K\left(1+\|\hat{x}(t(k))\|^2\right)$.

3.1 Characterizing limits, in $C([0,T],\mathbb{R}^d)$, of the rescaled trajectories

We do not provide proofs for the first three lemmas since they can be found in **Borkar** [10] or **Benaïm**, **Hofbauer and Sorin** [7]. The first two lemmas essentially state that the rescaled martingale noise converges almost surely.

Lemma 1.
$$\sup_{t \in [0,T]} E \|\hat{x}(t)\|^2 < \infty.$$

Lemma 2. The rescaled sequence $\{\hat{\zeta}_n\}_{n\geq 1}$, where $\hat{\zeta}_n = \sum_{k=0}^{n-1} a(k) \hat{M}_{k+1}$, is convergent almost surely.

The rest of the lemmas are needed to prove the stability theorem, Theorem 1. We begin by showing that the rescaled trajectories are bounded almost surely.

Lemma 3.
$$\sup_{t \in [0,\infty)} ||\hat{x}(t)|| < \infty \ a.s.$$

As stated earlier we omit the proof of the above stated lemma and establish a couple of notations used later. Let $A = \{\omega \mid \{\hat{\zeta}_n(\omega)\}_{n \geq 1} \ converges\}$. Since $\hat{\zeta}_n$, $n \geq 1$, converges on A, there exists $M_\omega < \infty$, possibly sample path dependent, such that $\|\sum_{l=0}^{k-1} a(m(n)+l)\hat{M}_{m(n)+l+1}\| \leq M_w$, where M_ω is independent of n and k. Also, let $\sup_{t\geq 0} \|\hat{x}(t)\| \leq K_\omega$, where $K_\omega := (1+M_\omega+(T+1)K) \, e^{K(T+1)}$ is also a constant that is sample path dependent.

Let $x^n(t)$, $t \in [0, T]$ be the solution (upto time T) to $\dot{x}^n(t) = \hat{y}(T_n + t)$, with the initial condition $x^n(0) = \hat{x}(T_n)$. Clearly, we have

$$x^{n}(t) = \hat{x}(T_{n}) + \int_{0}^{t} \hat{y}(T_{n} + z) dz.$$
 (4)

The following two lemmas are inspired by ideas from **Benaïm**, **Hofbauer** and **Sorin** [7] as well as **Borkar** [10]. In the lemma that follows we show that the limit sets of $\{x^n(\cdot) \mid n \geq 0\}$ and $\{\hat{x}(T_n+\cdot) \mid n \geq 0\}$ coincide. We seek limits in $C([0,T],\mathbb{R}^d)$.

Lemma 4.
$$\lim_{n\to\infty} \sup_{t\in[T_n,T_n+T]} ||x^n(t) - \hat{x}(t)|| = 0 \ a.s.$$

Proof. Let $t \in [t(m(n) + k), t(m(n) + k + 1))$ and $t(m(n) + k + 1) \le T_{n+1}$. We first assume that

 $t(m(n) + k + 1) < T_{n+1}$. We have the following:

$$\hat{x}(t) = \left(\frac{t(m(n) + k + 1) - t}{a(m(n) + k)}\right) \hat{x}(t(m(n) + k)) + \left(\frac{t - t(m(n) + k)}{a(m(n) + k)}\right) \hat{x}(t(m(n) + k + 1)).$$

Substituting for $\hat{x}(t(m(n) + k + 1))$ in the above equation we get:

$$\begin{split} \hat{x}(t) &= \left(\frac{t(m(n)+k+1)-t}{a(m(n)+k)}\right) \hat{x}(t(m(n)+k)) + \left(\frac{t-t(m(n)+k)}{a(m(n)+k)}\right) \\ & \left(\hat{x}(t(m(n)+k)) + a(m(n)+k)\left(\hat{y}(t(m(n)+k)) + \hat{M}_{m(n)+k+1}\right)\right), \end{split}$$

hence,

$$\hat{x}(t) = \hat{x}(t(m(n) + k)) + (t - t(m(n) + k)) \left(\hat{y}(t(m(n) + k)) + \hat{M}_{m(n) + k + 1}\right).$$

Unfolding $\hat{x}(t(m(n) + k))$ over k we get,

$$\hat{x}(t) = \hat{x}(T_n) + \sum_{l=0}^{k-1} a(m(n) + l) \left(\hat{y}(t(m(n) + l)) + \hat{M}_{m(n)+l+1} \right) + (t - t(m(n) + k)) \left(\hat{y}(t(m(n) + k)) + \hat{M}_{m(n)+k+1} \right).$$
 (5)

Now, we consider $x^n(t)$, i.e.,

$$x^{n}(t) = \hat{x}(T_{n}) + \int_{0}^{t} \hat{y}(T_{n} + z) dz.$$

Splitting the above integral, we get

$$x^{n}(t) = \hat{x}(T_{n}) + \sum_{l=0}^{k-1} \int_{t(m(n)+l)}^{t(m(n)+l+1)} \hat{y}(z) dz + \int_{t(m(n)+k)}^{t} \hat{y}(z) dz.$$

Thus,

$$x^{n}(t) = \hat{x}(T_{n}) + \sum_{l=0}^{k-1} a(m(n)+l)\hat{y}(t(m(n)+l)) + (t - t(m(n)+k))\hat{y}(t(m(n)+k)).$$
(6)

From (5) and (6), it follows that

$$||x^{n}(t) - \hat{x}(t)|| \le \left\| \sum_{l=0}^{k-1} a(m(n) + l) \hat{M}_{m(n)+l+1} \right\| + \left\| (t - t(m(n) + k)) \hat{M}_{m(n)+k+1} \right\|,$$

and hence,

$$||x^n(t) - \hat{x}(t)|| \le ||\hat{\zeta}_{m(n)+k} - \hat{\zeta}_{m(n)}|| + ||\hat{\zeta}_{m(n)+k+1} - \hat{\zeta}_{m(n)+k}||.$$

If $t(m(n)+k+1)=T_{n+1}$ then in the proof we may replace $\hat{x}(t(m(n)+k+1))$ with $\hat{x}(T_{n+1}^-)$. The arguments remain the same. Since $\hat{\zeta}_n$, $n \geq 1$, converges almost surely, the desired result follows.

The sets $\{x^n(t), t \in [0,T] \mid n \geq 0\}$ and $\{\hat{x}(T_n+t), t \in [0,T] \mid n \geq 0\}$ can be viewed as subsets of $C([0,T],\mathbb{R}^d)$. It can be shown that $\{x^n(t), t \in [0,T] \mid n \geq 0\}$ is equi-continuous and point-wise bounded. Thus from the Arzela-Ascoli theorem, $\{x^n(t), t \in [0,T] \mid n \geq 0\}$ is relatively compact. It follows from Lemma 4 that the set $\{\hat{x}(T_n+t), t \in [0,T] \mid n \geq 0\}$ is also relatively compact in $C([0,T],\mathbb{R}^d)$.

Lemma 5. Let $r(n) \uparrow \infty$, then any limit point of $\{\hat{x}(T_n + t), t \in [0, T] : n \geq 0\}$ is of the form $x(t) = x(0) + \int_0^t y(s) \, ds$, where $y : [0, T] \to \mathbb{R}^d$ is a measurable function and $y(t) \in h_\infty(x(t))$, $t \in [0, T]$.

Proof. We define the notation $[t] := max\{t(k) \mid t(k) \leq t\}, t \geq 0$. Let $t \in [T_n, T_{n+1})$, then $\hat{y}(t) \in h_{r(n)}(\hat{x}([t]))$ and $\|\hat{y}(t)\| \leq K (1 + \|\hat{x}([t])\|)$ since $h_{r(n)}$ is a Marchaud map (K) is the constant associated with the point-wise boundedness property). It follows from Lemma 3 that $\sup_{t \in [0,\infty)} \|\hat{y}(t)\| < \infty$ a.s. Using obser-

vations made earlier, we can deduce that there exists a sub-sequence of \mathbb{N} , say $\{l\} \subseteq \{n\}$, such that $\hat{x}(T_l + t) \to x(t)$ in $C\left([0,T],\mathbb{R}^d\right)$ and $\hat{y}(m(l)+\cdot) \to y(\cdot)$ weakly in $L_2\left([0,T],\mathbb{R}^d\right)$. From Lemma 4 it follows that $x^l(\cdot) \to x(\cdot)$ in $C\left([0,T],\mathbb{R}^d\right)$. Letting $r(l) \uparrow \infty$ in

$$x^{l}(t) = x^{l}(0) + \int_{0}^{t} \hat{y}(t(m(l) + z)) dz, \ t \in [0, T],$$

we get $x(t) = x(0) + \int_0^t y(z)dz$ for $t \in [0,T]$. Since $\|\hat{x}(T_n)\| \le 1$ we have $\|x(0)\| \le 1$.

Since $\hat{y}(T_l + \cdot) \to y(\cdot)$ weakly in $L_2([0,T], \mathbb{R}^d)$, there exists $\{l(k)\} \subseteq \{l\}$ such that

$$\frac{1}{N} \sum_{k=1}^{N} \hat{y}(T_{l(k)} + \cdot) \to y(\cdot) \text{ strongly in } L_2([0,T], \mathbb{R}^d).$$

Further, there exists $\{N(m)\}\subseteq\{N\}$ such that

$$\frac{1}{N(m)} \sum_{k=1}^{N(m)} \hat{y}(T_{l(k)} + \cdot) \to y(\cdot) \text{ a.e. on } [0, T].$$

Let us fix $t_0 \in \{t \mid \frac{1}{N(m)} \sum_{k=1}^{N(m)} \hat{y}(T_{l(k)} + t) \to y(t), t \in [0, T]\}, \text{ then}$

$$\lim_{N(m)\to\infty} \frac{1}{N(m)} \sum_{k=1}^{N(m)} \hat{y}(T_{l(k)} + t_0) = y(t_0).$$

Since $h_{\infty}(x(t_0))$ is convex and compact (Proposition 1), to show that $y(t_0) \in h_{\infty}(x(t_0))$ it is enough to prove that $\lim_{l(k)\to\infty} d\left(\hat{y}(T_{l(k)}+t_0),h_{\infty}(x(t_0))\right)=0$. If not, $\exists \ \epsilon>0$ and $\{n(k)\}\subseteq\{l(k)\}$ such that $d\left(\hat{y}(T_{n(k)}+t_0),h_{\infty}(x(t_0))\right)>\epsilon$. Since $\{\hat{y}(T_{n(k)}+t_0)\}_{k\geq 1}$ is norm bounded, it follows that there is a convergent sub-sequence. For the sake of convenience we assume that $\lim_{k\to\infty}\hat{y}(T_{n(k)}+t_0)=y$, for some $y\in\mathbb{R}^d$. Since $\hat{y}(T_{n(k)}+t_0)\in h_{r(n(k))}(\hat{x}([T_{n(k)}+t_0]))$ and $\lim_{k\to\infty}\hat{x}([T_{n(k)}+t_0])=x(t_0)$, it follows from assumption (A5) that $y\in h_{\infty}(x(t_0))$. This leads to a contradiction.

Note that in the statement of Lemma 5 we can replace $r(n) \uparrow \infty$ by $r(l) \uparrow \infty$, where $\{r(l)\}$ is a subsequence of $\{r(n)\}$. Specifically we can conclude that any limit point of $\{\hat{x}(T_k+t), t \in [0,T]\}_{\{k\}\subseteq \{n\}}$ in $C([0,T],\mathbb{R}^d)$, conditioned on $r(k) \uparrow \infty$, is of the form $x(t) = x(0) + \int_0^t y(z) dz$, where $y(t) \in h_\infty(x(t))$ for $t \in [0,T]$. It should be noted that $y(\cdot)$ may be sample path dependent. The following is an immediate consequence of Lemma 5.

Corollary 1. $\exists 1 < R_0 < \infty$ such that $\forall r(l) > R_0 ||\hat{x}(T_l + \cdot) - x(\cdot)|| < \delta_3 - \delta_2$, where $\{l\} \subseteq \mathbb{N}$ and $x(\cdot)$ is a solution (up to time T) of $\dot{x}(t) \in h_\infty(x(t))$ such that $||x(0)|| \le 1$. The form of $x(\cdot)$ is as given by Lemma 5.

Proof. Assume to the contrary that $\exists r(l) \uparrow \infty$ such that $\hat{x}(T_l + \cdot)$ is at least $\delta_3 - \delta_2$ away from any solution to the DI. It follows from Lemma 5 that there exists a subsequence of $\{\hat{x}(T_l + t), 0 \le t \le T : l \subseteq \mathbb{N}\}$ guaranteed to converge, in $C([0,T],\mathbb{R}^d)$, to a solution of $\dot{x}(t) \in h_\infty(x(t))$ such that $||x(0)|| \le 1$. This is a contradiction.

It is worth noting that R_0 may be sample path dependent. Since $T = T(\delta_2 - \delta_1) + 1$ we get $\|\hat{x}([T_l + T])\| < \delta_3$ for all T_l such that $\|\overline{x}(T_l)\| = r(l) > R_0$.

3.2 Stability theorem

We are now ready to prove the stability of a SRI given by (2) under the assumptions (A1)-(A5). If $\sup_n r(n)<\infty$, then the iterates are stable and there is nothing to prove. If on the other hand $\sup_n r(n)=\infty$, there exists $\{l\}\subseteq\{n\}$ such that $r(l)\uparrow\infty$. It follows from Lemma 5 that any limit point of $\{\hat{x}(T_l+t),t\in[0,T]:\{l\}\subseteq\{n\}\}$ is of the form $x(t)=x(0)+\int_0^t y(s)\ ds$, where $y(t)\in h_\infty(x(t))$ for $t\in[0,T]$. From assumption (A4), we have that $\|x(T)\|<\delta_2$. Since the time intervals are roughly T apart, for large values of r(n) we can conclude that $\|\hat{x}\left(T_{n+1}^-\right)\|<\delta_3$, where $\hat{x}\left(T_{n+1}^-\right)=\lim_{t\uparrow t(m(n+1))}\hat{x}(t),\ t\in[T_n,T_{n+1})$.

Theorem 1 (Stability Theorem for DI). Under assumptions (A1) - (A5), $\sup ||x_n|| < \infty$ a.s.

Proof. As explained earlier it is sufficient to consider the case when $\sup_{n} r(n) = \infty$. Let $\{l\} \subseteq \{n\}$ such that $r(l) \uparrow \infty$. Recall that $T_l = t(m(l))$ and that $|T_l + T| = \max\{t(k) \mid t(k) \leq T_l + T\}$.

We have $||x(T)|| < \delta_2$ since x(t) is a solution, up to time T, to the DI given by $\dot{x}(t) \in h_{\infty}(x(t))$ and we have fixed $T = T(\delta_2 - \delta_1) + 1$. From Lemma 5 we conclude that there exists N such that all of the following happen:

- (i) $m(l) \ge N \implies \|\hat{x}([T_l + T])\| < \delta_3$.
- (ii) $n \ge N \implies a(n) < \frac{\delta_4 \delta_3}{[K(1+K_\omega)+M_\omega]}$.
- (iii) $n > m \geq N \implies \|\hat{\zeta}_n \hat{\zeta}_m\| < M_{\omega}.$
- (iv) $m(l) \ge N \implies r(l) > R_0$.

In the above, R_0 is defined in the statement of Corollary 1 and K_{ω} , M_{ω} are explained in Lemma 3.

Recall that we chose $\sup_{x\in\mathcal{A}}||x||=\delta_1<\delta_2<\delta_3<\delta_4<1$ in Section 2.2. Let $m(l)\geq N$ and t(m(l+1))=t(m(l)+k+1) for some $k\geq 0$. Clearly from the manner in which the T_n sequence is defined, we have $t(m(l)+k)=[T_l+T]$. As defined earlier $\hat{x}(T_{n+1}^-)=\lim_{t\uparrow t(m(n+1))}\hat{x}(t),\ t\in [T_n,T_{n+1})$ and $n\geq 0$. Consider the equation

$$\hat{x}(T_{l+1}^-) \ = \ \hat{x}(t(m(l)+k)) \ + \ a(m(l)+k) \left(\hat{y}(t(m(l)+k)) + \hat{M}_{m(l)+k+1} \right).$$

Taking norms on both sides we get,

$$\|\hat{x}(T_{l+1}^-)\| \le \|\hat{x}(t(m(l)+k))\| + a(m(l)+k)\|\hat{y}(t(m(l)+k))\| + a(m(l)+k)\|\hat{M}_{m(l)+k+1}\|$$

From the way we have chosen N we conclude that:

$$\|\hat{y}(t(m(l)+k))\| \le K(1+\|\hat{x}(t(m(l)+k)\|) \le K(1+K_{\omega}) \text{ and that}$$

 $\|\hat{M}_{m(l)+k+1}\| = \|\hat{\zeta}_{m(l)+k+1} - \hat{\zeta}_{m(l)+k}\| \le M_{\omega}.$

Thus we have that.

$$\|\hat{x}(T_{l+1}^-)\| \le \|\hat{x}(t(m(l)+k))\| + a(m(l)+k)(K(1+K_\omega)+M_\omega).$$

Finally we have that $\|\hat{x}(T_{l+1}^-)\| < \delta_4$ and

$$\frac{\|\overline{x}(T_{l+1})\|}{\|\overline{x}(T_l)\|} = \frac{\|\hat{x}(T_{l+1}^-)\|}{\|\hat{x}(T_l)\|} < \delta_4 < 1.$$
 (7)

It follows from (7) that $\|\overline{x}(T_{n+1})\| < \delta_4 \|\overline{x}(T_n)\|$ if $\|\overline{x}(T_n)\| > R_0$. From Corollary 1 and the aforementioned we get that the trajectory falls at an exponential rate till it enters $\overline{B}_{R_0}(0)$. Let $t \leq T_l$, $t \in [T_n, T_{n+1})$ and $n+1 \leq l$, be the last time that $\overline{x}(t)$ jumps from $\overline{B}_{R_0}(0)$ to the outside of the ball. It follows that $\|\overline{x}(T_{n+1})\| \geq \|\overline{x}(T_l)\|$. Since $r(l) \uparrow \infty$, $\overline{x}(t)$ would be forced to make larger and larger jumps within an interval of T+1. This leads to a contradiction since the maximum jump within any fixed time interval can be bounded using the Gronwall inequality.

We now state one of the main theorems of this paper.

Theorem 2. Under assumptions (A1) - (A5), almost surely, the sequence $\{x_n\}_{n\geq 0}$ generated by the stochastic recursive inclusion, given by (2), is bounded and converges to a closed, connected, internally chain transitive and invariant set of $\dot{x}(t) \in h(x(t))$.

Proof. The stability of the iterates is shown in Theorem 1. The convergence can be proved under assumptions (A1) - (A3) and the stability of the iterates in exactly the same manner as in *Theorem 3.6 & Lemma 3.8* of **Benaïm**, **Hofbauer and Sorin** [7].

We have thus far shown that under assumptions (A1) - (A5) the SRI given by (2) is stable and converges to a closed, connected, internally chain transitive and invariant set.

3.3 Stability theorem under modified assumptions

In (A4) we assumed that $Liminf_{c\to\infty}h_c(x)$ is nonempty for all $x\in\mathbb{R}^d$. In this section we shall develop a stability criterion for the case when we no longer make such an assumption. In other words, we work with a modified version of assumption (A4) that we call (A6).

Modification of Assumption (A4)

Recall the following SRI:

$$x_{n+1} = x_n + a(n)[y_n + M_{n+1}], \text{ for } n \ge 0.$$
 (8)

Since h_c is point-wise bounded for each $c \ge 1$, we have $\sup_{y \in h_c(x)} \|y\| \le K(1 + \|x\|)$,

where $x \in \mathbb{R}^d$ (see Proposition 1). This implies that $\{y_c\}_{c \geq 1}$, where $y_c \in h_c(x)$, has at least one convergent subsequence. It follows from the definition of upper-limit of a sequence of sets (see Section 2.1) that $Limsup_{c\to\infty}h_c(x)$ is non-empty for every $x \in \mathbb{R}^d$. It is worth noting that $Liminf_{c\to\infty}h_c(x) \subseteq Limsup_{c\to\infty}h_c(x)$ for every $x \in \mathbb{R}^d$. Another important point to consider is that the lower-limits of sequences of sets are harder to compute than their upper-limits, see **Aubin** [3] for more details.

Recall that $h_c(x) = \{y \mid cy \in h(cx)\}$, where $x \in \mathbb{R}^d$ and $c \geq 1$. Clearly the upper-limit, $\underset{c \to \infty}{Limsup_{c \to \infty}} h_c(x) = \{y \mid \underset{c \to \infty}{\underline{lim}} d(y, h_c(x)) = 0\}$ is nonempty for every $x \in \mathbb{R}^d$. For $A \subseteq \mathbb{R}^d$, $\overline{co}(A)$ denotes the closure of the convex hull of A, i.e., the closure of the smallest convex set containing A.

Define
$$h_{\infty}(x) := \overline{co} \left(Limsup_{c \to \infty} h_{c}(x) \right)$$
.

Below we state the modification of assumption (A4) that we call (A6).

(A6) The differential inclusion $\dot{x}(t) \in h_{\infty}(x(t))$ has an attracting set $A \subset B_1(0)$ and $\overline{B}_1(0)$ is a subset of some fundamental neighborhood of A.

Note that in (A4), $h_{\infty}(x) := \overline{Liminf_{c\to\infty} h_c(x)}$ while in (A6), $h_{\infty}(x) := \overline{co} (Limsup_{c\to\infty} h_c(x))$. In this section we shall work with this new definition of h_{∞} .

Proposition 2. h_{∞} is a Marchaud map.

Proof. From the definition of h_{∞} it follows that $h_{\infty}(x)$ is convex, compact for all $x \in \mathbb{R}^d$ and h_{∞} is point-wise bounded. It is left to prove that h_{∞} is an upper-semicontinuous map.

Let $x_n \to x$, $y_n \to y$ and $y_n \in h_{\infty}(x_n)$, for all $n \geq 1$. We need to show that $y \in h_{\infty}(x)$. We present a proof by contradiction. Since $h_{\infty}(x)$ is convex and compact, $y \notin h_{\infty}(x)$ implies that there exists a linear functional on \mathbb{R}^d , say f, such that $\sup_{z \in h_{\infty}(x)} f(z) \leq \alpha - \epsilon$ and $f(y) \geq \alpha + \epsilon$, for some $\alpha \in \mathbb{R}$

and $\epsilon > 0$. Since $y_n \to y$, there exists N > 0 such that for all $n \geq N$, $f(y_n) \geq \alpha + \frac{\epsilon}{2}$. In other words, $h_{\infty}(x) \cap [f \geq \alpha + \frac{\epsilon}{2}] \neq \phi$ for all $n \geq N$. We use the notation $[f \geq a]$ to denote the set $\{x \mid f(x) \geq a\}$. For the sake of convenience let us denote the set $Limsup_{c \to \infty} h_c(x)$ by A(x), where $x \in \mathbb{R}^d$. We claim that $A(x_n) \cap [f \geq \alpha + \frac{\epsilon}{2}] \neq \phi$ for all $n \geq N$. We prove this claim later, for now we assume that the claim is true and proceed. Pick $z_n \in A(x_n) \cap [f \geq \alpha + \frac{\epsilon}{2}]$ for each $n \geq N$. It can be shown that $\{z_n\}_{n \geq N}$ is norm bounded and hence contains a convergent subsequence, $\{z_{n(k)}\}_{k \geq 1} \subseteq \{z_n\}_{n \geq N}$. Let $\lim_{k \to \infty} z_{n(k)} = z$. Since $z_{n(k)} \in Limsup_{c \to \infty}(h_c(x_{n(k)}))$, $\exists \ c_{n(k)} \in \mathbb{N}$ such that $\|w_{n(k)} - z_{n(k)}\| < \frac{1}{n(k)}$, where $w_{n(k)} \in h_{c_{n(k)}}(x_{n(k)})$. We choose the sequence $\{c_{n(k)}\}_{k \geq 1}$ such that $c_{n(k+1)} > c_{n(k)}$ for each $k \geq 1$.

We have the following: $c_{n(k)} \uparrow \infty$, $x_{n(k)} \to x$, $w_{n(k)} \to z$ and $w_{n(k)} \in h_{c_{n(k)}}(x_{n(k)})$, for all $k \geq 1$. It follows from assumption (A5) that $z \in h_{\infty}(x)$. Since $z_{n(k)} \to z$ and $f(z_{n(k)}) \geq \alpha + \frac{\epsilon}{2}$ for each $k \geq 1$, we have that $f(z) \geq \alpha + \frac{\epsilon}{2}$. This contradicts the earlier conclusion that $\sup_{z \in h_{\infty}(x)} f(z) \leq \alpha - \epsilon$.

It remains to prove that $A(x_n) \cap [f \geq \alpha + \frac{\epsilon}{2}] \neq \phi$ for all $n \geq N$. If this were not true, then $\exists \{m(k)\}_{k \geq 1} \subseteq \{n \geq N\}$ such that $A(x_{m(k)}) \subseteq [f < \alpha + \frac{\epsilon}{2}]$ for all k. It follows that

 $h_{\infty}(x_{m(k)}) = \overline{co}(A(x_{m(k)})) \subseteq [f \le \alpha + \frac{\epsilon}{2}]$ for each $k \ge 1$. Since $y_{n(k)} \to y$, $\exists N_1$ such that for all $n(k) \ge N_1$, $f(y_{n(k)}) \ge \alpha + \frac{3\epsilon}{4}$. This is a contradiction.

We are now ready to state the second stability theorem for an SRI given by (8) under a modified set of assumptions. We retain assumptions (A1)-(A3), replace (A4) by (A6) and finally in (A5) we let $h_{\infty}(x) := \overline{co} (Limsup_{c \to \infty} h_{c}(x))$. We state the theorem under these updated set of assumptions.

Theorem 3 (Stability Theorem for DI #2). Under assumptions (A1) - (A3), (A5) (with $h_{\infty}(x) := \overline{co}(Limsup_{c\to\infty}h_c(x))$) and (A6), almost surely the sequence $\{x_n\}_{n\geq 0}$ generated by the stochastic recursive inclusion, given by (8) is bounded and converges to a closed, connected internally chain transitive invariant set of $\dot{x}(t) \in h(x(t))$.

Proof. The statements of Lemmas 1–5 hold true even when $h_{\infty} := \overline{co}$ (Limsup_{c→∞} $h_c(x)$) and (A5) is interpreted as explained earlier. The stability of the iterates can be proven in an identical manner to the proof of Theorem 1. Next, we invoke Theorem 3.6 & Lemma 3.8 of Benaïm, Hofbauer and Sorin [7] to conclude that the iterates converge to a closed, connected, internally chain transitive and invariant set of $\dot{x}(t) \in h(x(t))$.

Remark 1. Assumptions (A4) and (A6) required that $\dot{x}(t) \in h_{\infty}(x(t))$ have an attractor set inside $B_1(0)$ (the open unit ball). Further, it required $\overline{B}_1(0)$ to be in its fundamental neighborhood. Note that $h_{\infty}(x)$ is defined as $\overline{Liminf_{c\to\infty}} \ h_c(x)$ when using (A4) and it is defined as \overline{co} (Limsup_{c\to\infty} $h_c(x)$) when using (A6). Consider the following generalization of (A4)/(A6).

(A4)'/(A6)': $\dot{x}(t) \in h_{\infty}(x(t))$ has an attractor set A such that $A \subseteq B_a(0)$ and $\overline{B}_a(0)$ is a subset of its fundamental neighborhood, where $0 \le a < \infty$.

Note that a could be greater than 1, further since \mathcal{A} is compact by definition, a is finite. A sufficient condition for (A4)'/(A6)' is when \mathcal{A} is a globally attracting, Lyapunov stable set associated with $\dot{x}(t) \in h_{\infty}(x(t))$. In this case any compact set is a fundamental neighborhood of \mathcal{A} .

At the beginning of Section 3 we constructed the rescaled trajectory by projecting onto the unit ball around the origin. In order to use (A4)'/(A6)' we build the rescaled trajectory by projecting onto $\overline{B}_a(0)$ instead. We can modify the proofs such that the statements of Theorems 2 and 3 remain true under assumptions (A1) - (A3), (A4)'/(A6)' and (A5).

Remark 2. The advantage of using (A4)'/(A6)' is that one can conclude the stability of the iterates by merely possessing the knowledge that the associated DI of the infinity system has a global attractor set. Consider the following trivial example of a stochastic gradient descent algorithm with linear gradient function of the from -(Ax+b). The corresponding infinity system, $\dot{x}(t) = -Ax$, is clearly "related" to the associated o.d.e. $\dot{x}(t) = -(Ax+b)$. Specifically, if there was a unique global minimizer then both the aforementioned o.d.e.'s have a global attractor which in turn implies the stability of the iterates as discussed before. This trivial example also illustrates a finer point that h_{∞} and h could be related, hence information about h could help us ascertain if (A4)'/(A6)' is satisfied. Whenever possible one could also construct Lyapunov functions to ascertain the same. While we did not consider Lyapunov-type conditions for stability, it would be interesting to extend the Lyapunov-type stability conditions developed for SRE's by Andrieu, Priouret and Moulines [1] to include SRI's.

4 Extensions to the stability theorem of Borkar and Meyn

We begin this section by listing the assumptions (See Section 2 of [13]) and statement of the Borkar-Meyn Theorem (See Section 2.1 of [13]). The notations used are consistent with those of equation (1).

- (BM1) (i) The function $h: \mathbb{R}^d \to \mathbb{R}^d$ is Lipschitz continuous, with Lipschitz constant L. There exists a function $h_{\infty}: \mathbb{R}^d \to \mathbb{R}^d$ such that $\lim_{c \to \infty} \frac{h(cx)}{c} = h_{\infty}(x)$, for each $x \in \mathbb{R}^d$.
 - (ii) $h_c \to h_\infty$ uniformly on compacts, as $c \to \infty$.
 - (iii) The o.d.e. $\dot{x}(t) = h_{\infty}(x(t))$ has the origin as the unique globally asymptotically stable equilibrium.
- (BM2) $\{a(n)\}_{n\geq 0}$ is a scalar sequence such that: $a(n)\geq 0, \sum_{n\geq 0}a(n)=\infty$ and $\sum_{n\geq 0}a(n)^2<\infty$. Without loss of generality, we also let $\sup_n a(n)\leq 1$.
- (BM3) $\{M_n\}_{n\geq 1}$ is a martingale difference sequence with respect to the filtration $\mathcal{F}_n := \sigma\left(x_0, M_1, \ldots, M_n\right), \ n\geq 0$. Thus, $E\left[M_{n+1}|\mathcal{F}_n\right] = 0$ a.s., $\forall \ n\geq 0$. $\{M_n\}$ is also square integrable with $E[\|M_{n+1}\|^2|\mathcal{F}_n] \leq L\left(1+\|x_n\|^2\right)$, for some constant L>0. Without loss of generality, assume that the same constant, L, works for both (BM1)(i) and (BM3).

Theorem 4 (Borkar-Meyn Theorem). Suppose (BM1)-(BM3) hold. Then $\sup_n ||x_n|| < \infty$ almost surely. Further, the sequence $\{x_n\}$ converges almost surely to a (possibly sample path dependent) compact connected internally chain transitive invariant set of $\dot{x}(t) = h(x(t))$.

In what follows we illustrate a weakening of (BM1) - (BM3) stated above using Theorems 2 & 3. Note that (BM2) is the standard step-size assumption while (BM3) is the assumption on the martingale difference noise; we endeavor to weaken (BM1).

4.1 Superfluity of (BM1)(ii) as a consequence of Theorem 2

In this section we discuss in brief how the *Borkar-Meyn Theorem* (Theorem 4) can be proven under (BM1)(i), (iii), (BM2) and (BM3). In other words, we show that (BM1)(ii) is superfluous. In this direction we begin by showing the following: A recursion given by (1) satisfies (BM1)(i), (iii), (BM2) and (BM3) \Rightarrow (1) satisfies (A1) - (A5) of Section 2.2. The following implications are straightforward: (BM1)(i), $(iii) \Rightarrow (A1) \& (A4)$; $(BM2) \Rightarrow (A2)$; $(BM3) \Rightarrow (A3)$. We now show (BM1)(i), $(iii) \Rightarrow (A5)$. Given $x_n \to x$, $c_n \uparrow \infty$ and $h_{c_n}(x_n) \to y$ we need to show $y = h_{\infty}(x)$. We have the following:

$$||h_{c_n}(x_n) - h_{\infty}(x)|| \le ||h_{c_n}(x_n) - h_{c_n}(x)|| + ||h_{c_n}(x) - h_{\infty}(x)||.$$

If h is Lipschitz with constant L then it can be shown that h_c $(h_c: x \mapsto \frac{h(cx)}{c}, x \in \mathbb{R}^d)$ is Lipschitz, for every $c \ge 1$, with the same constant. Further, $h_{c_n}(x) \to 0$

 $h_{\infty}(x)$ as $c_n \uparrow \infty$. Taking limits $(c_n \uparrow \infty)$ on both sides of the above equation gives $\lim_{c_n \uparrow \infty} h_{c_n}(x_n) = h_{\infty}(x)$ as required. Since (A1) - (A5) are satisfied it follows from Theorem 2 that a SRE satisfying (BM1)(i), (iii), (BM2), (BM3) is stable and converges to a closed, connected, internally chain transitive and invariant set of $\dot{x}(t) = h(x(t))$ (Theorem 4).

We discuss in brief how we work around using (BM1)(ii) in proving the Borkar-Meyn Theorem. The notations used herein are consistent with those found in Chapter 3 of Borkar [10]. We list a few below for easy reference.

- 1. $\phi_n(\cdot, x)$ denotes the solution to $\dot{x}(t) \in h_{r(n)}(x(t))$ with initial value x.
- 2. $\phi_{\infty}(\cdot, x)$ denotes the solution to $\dot{x}(t) \in h_{\infty}(x(t))$ with initial value x.
- 3. $x^n(t)$, $t \in [0,T]$ denotes the solution to $\dot{x}^n(t) = h_{r(n)}(\hat{x}(T_n+t))$ with initial value $x^n(0) = \hat{x}(T_n)$. Then $x^n(t) = \phi_n(t,\hat{x}(T_n))$, $t \in [0,T]$.

In proving the Borkar-Meyn Theorem as outlined in [13] (BM1)(ii) is used to show that for large values of r(n), $\phi_n(t, \hat{x}(T_n))$ is 'close' to $\phi_\infty(t, \hat{x}(T_n))$, $t \in [0, T]$. In this paper we deviate from [13] in the definition of $x^n(t)$, $t \in [0, T]$, here $x^n(\cdot)$ denotes the solution up to time T of $\dot{x}^n(t) = \hat{y}(T_n + t) = h_{r(n)}(\hat{x}([T_n + t]))$ with $x^n(0) = \hat{x}(T_n)$, where $[\cdot]$ is defined in Lemma 5. In other words, we have the following:

$$x^{n}(t) = \hat{x}(T_{n}) + \sum_{l=0}^{k-1} \int_{t(m(n)+l)}^{t(m(n)+l+1)} \hat{y}(z) dz + \int_{t(m(n)+k)}^{t} \hat{y}(z) dz.$$

For $t \in [t_n, t_{n+1})$, $\hat{y}(t)$ is a constant and equals $\hat{y}(t_n)$. We get the following:

$$x^{n}(t) = \hat{x}(T_{n}) + \sum_{l=0}^{k-1} a(m(n)+l)h_{r(n)}\left(\hat{x}([t(m(n)+l)])\right) + (t-t(m(n)+k))h_{r(n)}\left(\hat{x}([t(m(n)+k)])\right).$$

The proof now proceeds along the lines of Section 3.2 *i.e.*, Lemmas 1 - 5 and Theorem 1; we essentially show the following: If $r(n) \uparrow \infty$ then the T-length trajectories given by $\{x^n(\cdot)\}_{n\geq 0}$ have $\phi_{\infty}(x,t)$, $t\in [0,T]$, as the limit point in $C([0,T],\mathbb{R}^d)$, where $x\in \overline{B}_1(0)$. This is proven in Lemmas 4 and 5, the proofs of which do not require (BM1)(ii).

4.2 Further weakening of (BM1) as a consequence of Theorem 3

In this section we use the second stability theorem (Theorem 3) to answer the following question: If $\lim_{c\to\infty} h_c(x)$ does not exist for all $x\in\mathbb{R}^d$, then what are the sufficient conditions for the stability and convergence of the algorithm?

Taking our cue from assumption (A6), we replace (BM1) with the following assumption, call it (BM4).

(BM4)(i) The function $h: \mathbb{R}^d \to \mathbb{R}^d$ is Lipschitz continuous, with Lipschitz constant L. Define the set-valued map, $h_{\infty}(x) := \overline{co}(Limsup_{c\to\infty}\{h_c(x)\})$, where $x \in \mathbb{R}^d$.

Note that
$$Limsup_{c\to\infty}\{h_c(x)\}=\{y\mid \underline{\lim}_{c\to\infty}\|h_c(x)-y\|=0\}.$$

(BM4)(ii) $\dot{x}(t) \in h_{\infty}(x(t))$ has an attracting set, \mathcal{A} , with $\overline{B}_1(0)$ as a subset of its fundamental neighborhood. This attracting set is such that $\mathcal{A} \subseteq B_1(0)$.

Observe that $Limsup_{c\to\infty}\{h_c(x)\}=\lim_{c\to\infty}h_c(x)$ when $\lim_{c\to\infty}h_c(x)$ exists. Recall the definition of Limsup, the upper-limit of a sequence of sets, from Section 2.1. It can be shown that if a recursion given by (1) satisfies assumptions (BM1)(i) and (BM1)(ii) then it also satisfies (BM4)(i), (ii). Assumption (BM4) unifies the two possible cases: when the limit of h_c , as $c\to\infty$, exists for each $x\in\mathbb{R}^d$ and when it does not.

We claim that a recursion given by (1), satisfying assumptions (BM2), (BM3) and (BM4) will also satisfy (A1)-(A3), (A6) and (A5) (see section 3.3). From Theorem 3 it follows that the iterates are stable and converge to a closed, connected, internally chain transitive and invariant set of $\dot{x}(t) = h(x(t))$. The following generalization of the *Borkar-Meyn Theorem* is a direct consequence of Theorem 3.

Corollary 2 (Generalized Borkar-Meyn Theorem). Under assumptions (BM2), (BM3) and (BM4), almost surely the sequence $\{x_n\}_{n\geq 0}$ generated by the stochastic recursive equation (1), is bounded and converges to a closed, connected, internally chain transitive and invariant set of $\dot{x}(t) = h(x(t))$.

Proof. Assumptions (A1)-(A3) and (A6) follow directly from (BM2), (BM3) and (BM4). We show that (A5) is also satisfied. Let $c_n \uparrow \infty$, $x_n \to x$, $y_n \to y$ and $y_n \in h_{c_n}(x_n)$ (here $y_n = h_{c_n}(x_n)$), $\forall n \geq 1$. It can be shown that $\|h_{c_n}(x_n) - h_{c_n}(x)\| \leq L\|x_n - x\|$. Hence we get that $h_{c_n}(x) \to y$. In other words, $\lim_{c \to \infty} \|h_c(x) - y\| = 0$. Hence we have $y \in h_{\infty}(x)$. The claim now follows from Theorem 3.

5 Applications: The problem of approximate drifts & stochastic gradient descent

5.1 The problem of approximate drifts

Let us recall the standard SRE:

$$x_{n+1} = x_n + a(n) \left(h(x_n) + M_{n+1} \right), \tag{9}$$

where $h: \mathbb{R}^d \longrightarrow \mathbb{R}^d$ is Lipschitz continuous, $\{a(n)\}_{n\geq 0}$ is the step-size sequence and $\{M_n\}_{n\geq 1}$ is the noise sequence.

The function h is colloquially referred to as the drift. In many applications the drift function cannot be calculated accurately. This is referred to as the approximate drift problem. For more details the reader is referred to *Chapter 5.3* of *Borkar* [10]. Suppose the room for error is at most $\epsilon(>0)$ then such an algorithm can be characterized by the following stochastic recursive inclusion:

$$x_{n+1} = x_n + a(n) (y_n + M_{n+1}), (10)$$

where $y_n \in h(x_n) + \overline{B}_{\epsilon}(0)$ is an estimate of $h(x_n)$ and $\overline{B}_{\epsilon}(0)$ is the closed ball of radius ϵ around the origin. We define a new set-valued map called the approximate drift by $H(x) := h(x) + \overline{B}_{\epsilon}(0)$ for each $x \in \mathbb{R}^d$. In the following discussion we assume that $\epsilon \geq 0$. When $\epsilon = 0$, the approximate drift algorithm described by (10) is really the SRE given by (9).

In this section we show the following: If (9) satisfies (BM2), (BM3) and (BM4) then the corresponding approximate drift version given by (10) satisfies (A1)-(A5). For details on (BM2) and (BM3) see Section 4.1; see Section 4.2 for (BM4). We then invoke Theorem 3 to conclude that the iterates converge to a closed, connected, internally chain transitive and invariant set associated with $\dot{x}(t) \in h(x(t)) + \overline{B}_{\epsilon}(0) (= H(x(t)))$.

For the remainder of this section it is assumed that (9) satisfies (BM2), (BM3) and (BM4).

Proposition 3. $H(x) = h(x) + \overline{B}_{\epsilon}(0)$ is a Marchaud map. Further, recursion (10) satisfies (A1), (A2) and (A3).

Proof. Since $\overline{B}_{\epsilon}(0)$ is convex and compact, it follows that H(x) is convex and compact for each $x \in \mathbb{R}^d$. Fix $x \in \mathbb{R}^d$ and $y \in H(x)$, then $||y|| \le ||h(x)|| + \epsilon$ and $||y|| \le ||h(0)|| + L||x - 0|| + \epsilon$ since h is Lipschitz continuous with Lipschitz constant L. If we set $K := (||h(0)|| + \epsilon) \lor L$, then we get $||y|| \le K (1 + ||x||)$. This shows that H is point-wise bounded. To show the upper semi-continuity of H assume $\lim_{n \to \infty} x_n = x$, $\lim_{n \to \infty} y_n = y$ and $y_n \in H(x_n)$ for each $n \ge 1$. For all $n \ge 1$, $y_n = h(x_n) + z_n$ for some $z_n \in \overline{B}_{\epsilon}(0)$. Further, $h(x_n) \to h(x)$ as $x_n \to x$. Since both $\{y_n\}_{n\ge 1}$ and $\{h(x_n)\}_{n\ge 1}$ are convergent sequences, $\{z_n\}_{n\ge 1}$ is also convergent. Let $z := \lim_{n \to \infty} z_n$; z is such that $z \in \overline{B}_{\epsilon}(0)$ since $\overline{B}_{\epsilon}(0)$ is compact. Taking limits on both sides of $y_n = h(x_n) + z_n$, we get y = h(x) + z. Thus $y \in H(x)$.

Since (10) is assumed to satisfy (BM2) and (BM3) it trivially follows that it satisfies (A2) and (A3).

Before showing that (10) satisfies (A4), we construct the following family of set-valued maps:

$$H_c(x) := \left\{ \frac{h(cx)}{c} + \frac{y}{c} \mid y \in \overline{B}_{\epsilon}(0) \right\}, \tag{11}$$

where $c \geq 1$ and $x \in \mathbb{R}^d$. In other words, $H_c(x) = h_c(x) + \overline{B}_{\epsilon/c}(0)$ for each $x \in \mathbb{R}^d$.

Proposition 4. (10) satisfies (A6).

Proof. To prove this it is enough to show that $H_{\infty}(x) = h_{\infty}(x)$, where $H_{\infty}(x) := Limsup_{c\to\infty}H_c(x)$ and $h_{\infty}(x) := Limsup_{c\to\infty}h_c(x)$. Since $\dot{x}(t) \in h_{\infty}(x(t))$ satisfies (BM4)(ii) it trivially follows that (A6) is satisfied by (10). Note that (BM4)(ii) and (A6) essentially say the same thing.

First we show $h_{\infty}(x) \subseteq H_{\infty}(x)$ for every $x \in \mathbb{R}^d$. Let $y \in h_{\infty}(x)$, $\exists c_n \uparrow \infty$ such that $h_{c_n} \to y$ as $c_n \uparrow \infty$. Since $h_{c_n}(x) \in H_{c_n}(x)$ it follows from the definition of Limsup that $y \in H_{\infty}(x)$. To show $H_{\infty}(x) \subseteq h_{\infty}(x)$ we start by assuming the negation i.e., for some $x \in \mathbb{R}^d \exists y \in H_{\infty}(x)$ such that $y \notin h_{\infty}(x)$. Let $c_n \uparrow \infty$ and $y_n \in H_{c_n}(x_n)$ such that $\lim_{c_n \uparrow \infty} y_n = y$. Since $\|y_n - h_{c_n}(x_n)\| \le \frac{\epsilon}{c_n}$ we have $\lim_{c_n \uparrow \infty} h_{c_n}(x_n) = y$. We have the following:

$$||y - h_{c_n}(x)|| \le ||y - h_{c_n}(x_n)|| + ||h_{c_n}(x_n) - h_{c_n}(x)||.$$

Taking limits on both sides we get that $||y - h_{c_n}(x)|| \to 0$ i.e., $y \in h_{\infty}(x)$. This is a contradiction.

Proposition 5. (10) satisfies (A5).

Proof. Given $c_n \uparrow \infty$, $x_n \to x$, $y_n \to y$ and $y_n \in H_{c_n}(x_n) \ \forall n$, we need to show that $y \in H_{\infty}(x)$. As in the proof of Proposition 4 we have $\lim_{\substack{c_n \uparrow \infty \\ c_n \uparrow \infty}} h_{c_n}(x_n) = y$. Since $\|h_{c_n}(x_n) - h_{c_n}(x)\| \le L \|x_n - x\|$ we have that $\lim_{\substack{c_n \uparrow \infty \\ c_n \uparrow \infty}} \|h_{c_n}(x_n) - h_{c_n}(x)\| = 0$ and $\lim_{\substack{c_n \uparrow \infty \\ c_n \uparrow \infty}} h_{c_n}(x) = y$. In other words, $y \in h_{\infty}(x)$. In Proposition 3 we have shown that $h_{\infty} \equiv H_{\infty}$ therefore $y \in H_{\infty}(x)$.

Corollary 3. If a SRE, given by (9), satisfies (BM2), (BM3) and (BM4)(i), (ii) then the corresponding approximate drift version given by (10) is stable almost surely. In addition, it converges to a closed, connected, invariant and internally chain transitive set of $\dot{x}(t) \in H(x(t))$, where $H(x) = h(x) + \overline{B}_{\epsilon}(0)$.

Proof. In Propositions 3, 4 and 5 we have shown that (9) satisfies (A1) – (A3), (A5), (A6); the statement now follows directly from Theorem 3.

Remark 3. In the context of (9), we have that h is Lipschitz and $h_c: x \mapsto \frac{h(cx)}{c}$. Supposing $\lim_{c \to \infty} h_c(x)$ exists for every $x \in \mathbb{R}^d$ (see (BM1)(i) in Section 4) then $\lim_{c \to \infty} h_c(x) = Limsup_{c \to \infty}\{h_c(x)\}$. Further, $Limsup_{c \to \infty}\{h_c(x)\}$ is non-empty for every $x \in \mathbb{R}^d$ (since $h_c(x) \leq K(1 + ||x||)$, $c \geq 1$), even if $\lim_{c \to \infty} h_c(x)$ does not exist for some $x \in \mathbb{R}^d$. Hence the analysis of the approximate drift problem in this section is all encompassing. The aforementioned is also the reason why in Section 4.2 we define $h_{\infty}(x) := \overline{co}(Limsup_{c \to \infty}\{h_c(x)\})$. It may be noted that we use $Limsup_{c \to \infty}\{h_c(x)\}$ instead of $Limsup_{c \to \infty}h_c(x)$ since Limsup acts on sets and h (in this context) is a function that is not set-valued. Finally, in Corollary 3 if we let $\epsilon = 0$ then we may derive Corollary 2.

5.2 Stochastic gradient descent

Stochastic gradient descent is a gradient descent optimization technique to find the minimum set of a (continuously) differentiable function. Suppose we want to find the minimum of $F: \mathbb{R}^d \to \mathbb{R}$ for which we can run the following SRE:

$$x_{n+1} = x_n - a(n)[\nabla F(x_n) + M_{n+1}], \tag{12}$$

where $\nabla F: \mathbb{R}^d \to \mathbb{R}^d$ is upper-semicontinuous and $\|\nabla F(x)\| \leq K(1+\|x\|)$ $\forall x \in \mathbb{R}^d$ (point-wise bounded). $\{a(n)\}_{n\geq 0}$ is the given step size sequence and $\{M_{n+1}\}_{n\geq 0}$ is the martingale difference noise sequence. If the assumptions of Benaïm, Hofbauer and Sorin [7] are satisfied by (12) then the iterates converge to a closed, connected, internally chain transitive and invariant set of $\dot{x}(t) = -\nabla F(x(t))$ which is also the minimum set of F. In this section we shall not distinguish between the asymptotic attracting set of $\dot{x}(t) = -\nabla F(x(t))$ and the minimum set of F.

As explained in Section 1, while implementing (12) one can only hope to calculate an approximate value of the gradient at each step. However, one has control over the "approximation error". This is typical when gradient estimators with fixed perturbation parameters are used, it could also be a consequence of the inherent computational capability of the computer used to run the algorithm. In reality one is running the following SRI:

$$x_{n+1} = x_n + a(n)[y_n + M_{n+1}], (13)$$

where $y_n \in -\nabla F(x_n) + \overline{B}_{\epsilon}(0)$ and $\epsilon > 0$ is the "approximation error". The following questions are natural:

- 1. Are the iterates stable?
- 2. If so, where do they converge?

Define the following set valued map, $H: x \mapsto -\nabla F(x) + \overline{B}_{\epsilon}(0)$. As in (11) we define $H_c(x) := \frac{-\nabla F(cx)}{c} + \overline{B}_{\epsilon/c}(0)$ and $H_{\infty}(x) := Limsup_{c\to\infty}H_c(x) = Limsup_{c\to\infty}\left\{\frac{-\nabla F(cx)}{c}\right\}$. Recall the definition of Limsup from Section 2.1.

Proposition 6. (13) satisfies (A1) i.e., H is a marchaud map.

Proof. Given $x_n \to x$, $y_n \to y$ and $y_n \in H(x_n) \, \forall n$, we need to show that $y \in H(x)$. For each n we have $y_n = -\nabla F(x_n) + z_n$, where $z_n \in \overline{B}_{\epsilon}(0)$. Since ∇F is point-wise bounded, it follows that $\{-\nabla F(x_n)\}$ is a bounded sequence. Let $\{n(m)\} \subseteq \mathbb{N}$ such that $\nabla F(x_{n(m)}) \to \nabla F(x)$, $y_{n(m)} \to y$. The subsequence $z_{n(m)} \to z$ for some $z \in \overline{B}_{\epsilon}(0)$ i.e.,

$$\left(-\nabla F(x_{n(m)}) + z_{n(m)}\right) \to \left(-\nabla F(x) + z\right) \in H(x).$$

If in addition to (A1), equation (13) also satisfies (A2), (A3), (A5) and (A6) then it follows from Theorem 3 that the iterates are stable and converge to a closed, connected, internally chain transitive and invariant set of $\dot{x}(t) \in (-\nabla F(x(t)) + \overline{B}_{\epsilon}(0))$.

Suppose F has the quadratic form $x^TAx+Bx+c$, where A is a positive definite matrix, B is some matrix and c is some vector. Then it can be shown that (A1), (A2), (A3), (A5) and (A6) are satisfied by (13) and the iterates are stable and converge to a closed, connected, internally chain transitive and invariant set of $\dot{x}(t) \in -(Ax(t)+B)+\overline{B}_{\epsilon}(0)$. If the comments in Remark 1 are incorporated i.e., we use (A6)' instead of (A6) then matrix A need not be positive definite anymore.

For the purpose of this discussion assume that ∇F is Lipschitz continuous. The graph of a set-valued map $H: \mathbb{R}^d \to \{\text{subsets of } \mathbb{R}^d\}$ is given by $Graph(H) = \{(x,y) \mid x \in \mathbb{R}^d, \ y \in H(x)\}$. It is easy to see that $Graph(-\nabla F) + \overline{B}_{\epsilon}(0) \subseteq N^{2\epsilon}(Graph(-\nabla F))$. Let us also assume that \mathcal{A} is the global attractor (minimum set of F) of $\dot{x}(t) = -\nabla F(x(t))$ then every compact subset of \mathbb{R}^d is its fundamental neighborhood. It follows from the stability of the iterates that they will remain within a compact subset, say \mathcal{U} , that may be sample path dependent. It follows from Theorem 2.1 of Benaïm, Hofbauer and Sorin [8] that for all $\delta > 0$ there exists $\epsilon > 0$ such that $\mathcal{A}^\delta \subseteq N^\delta(\mathcal{A})$ is the attractor set of $\dot{x}(t) \in -\nabla F(x(t)) + \overline{B}_{\epsilon}(0)$. Further, the fundamental neighborhood of \mathcal{A}^δ is \mathcal{U} itself. In other words, suppose we want to ensure convergence of the iterates to a $\delta - neighborhood$ of the minimum set \mathcal{A} then the "approximation error" should be at most ϵ (ϵ is dependent on δ).

6 Final discussion on the generality of our framework

As explained in Section 3, we run a projective scheme to show stability. In other words, time is divided into intervals of length T; the iterates are checked at the beginning of each time interval to see if they are outside the unit ball; all the iterates corresponding to $[T_n, T_{n+1})$ are scaled by $r(n) = ||x(T_n)|| \lor 1$ i.e., the iterates are projected onto the unit ball around the origin. For $t(m(n)) = T_n \le t(m(n) + k) < T_{n+1}$ we have the following re-scaled iterate:

$$\frac{\overline{x}(t(m(n)+k))}{r(n)} = \frac{\overline{x}(t(m(n)))}{r(n)} + \sum_{j=0}^{k-1} a(m(n)+j) \left[\frac{\overline{y}(t(m(n)+j))}{r(n)} + \frac{M_{m(n)+j+1}}{r(n)} \right].$$

In the above, $\frac{\overline{y}(t(m(n)+j))}{r(n)} \in h_{r(n)}\left(\frac{\overline{x}(t(m(n)+j))}{r(n)}\right)$. Since we have to worry about r(n) running off to infinity it is natural to define $h_{\infty}(x)$ to include all accumulation points of $\{h_c(x) \mid c \geq 1, c \to \infty\}$. This is precisely what the Limsup function (see Section 2.1) allows us to do. In Lemma 5 it was shown that the scaled iterates track a solution to $\dot{x}(t) \in h_{\infty}(x(t))$ provided the original iterates are unstable i.e., sup $r(n) = \infty$. Assumptions (A4)/(A6) were never used up to this point. At this stage it seems natural to impose restrictions on $\overline{x}(t) \in h_{\infty}(x(t))$ to elicit the stability of the original iterates.

As explained in Section 3.3 $Limsup_{c\to\infty}h_c(x)$ is non-empty for every $x\in\mathbb{R}^d$ since h is point-wise bounded. Further, $h_\infty\equiv \overline{co}\left(Limsup_{c\to\infty}h_c\right)$ is shown to be Marchaud and the $DI\ \dot{x}(t)\in h_\infty(x(t))$ has at least one solution. Assumption

(A6) is the restriction referred to in the previous paragraph that is imposed to elicit the stability of the original iterates. On a related note, if $Liminf_{c\to\infty}h_c$ were non-empty, then we define $h_{\infty} \equiv \overline{Liminf_{c\to\infty}h_c}$ and check if (A4) is satisfied

If the $DI \ \dot{x}(t) \in h_{\infty}(x(t))$ has global attractor inside $B_1(0)$, then this is a sufficient condition for (A6) to hold, it then follows from Theorem 3 that the original iterates are stable and converge to a closed connected internally chain transitive set associated with $\dot{x}(t) \in h(x(t))$. More generally, in lieu of Remark 1 it is sufficient that the DI has some global attractor, not necessarily inside the unit ball, since (A6)' will then hold. This in turn implies stability.

In case of the original Borkar-Meyn assumptions, (BM1)(i), (ii) (see Section 4) needed to be checked even before we could define h_{∞} while in our case we do not need any extra assumptions to define h_{∞} . As explained before, constructing a global Lyapunov function for h_{∞} is one of many sufficient conditions that guarantee (A4)'/(A6)'. In case of Lyapunov-type conditions for stability, additional properties of the constructed global Lyapunov function need to be verified before we get stability, see [1] for more details. However, to the best of our knowledge, there are no Lyapunov-type conditions that guarantee stability of stochastic approximation algorithms with set-valued mean fields (SRI), the class of algorithms dealt with in this paper. Hence our assumptions are general and relatively easy to verify.

7 Conclusions

An extension was presented to the theorem of Borkar and Meyn to include approximation algorithms with set-valued mean fields. Two different sets of sufficient conditions were presented that guarantee the 'stability and convergence' of stochastic recursive inclusions. As a consequence of Theorems 2 & 3, the original Borkar-Meyn theorem is shown to hold under weaker requirements. Further, as a consequence of Theorem 3, we obtained a solution to the "approximate drift" problem. Prior to this paper, there was no proof of stability of stochastic gradient descent algorithms that use constant-error gradient estimators. Hence we could only conclude that the iterates converge to a small neighborhood, say \overline{N} , of the minimum set with very high probability. In Section 5.2 we used our framework to show the stability of the aforementioned algorithm which in turn allowed us to conclude an almost sure convergence to \overline{N} .

An important future direction would be to extend these results to the case when the set-valued drift is governed by a Markov process in addition to the iterate sequence. For the case of stochastic approximations, such a situation has been considered in [[10], Chapter 6], where the Markov 'noise' is tackled using the 'natural timescale averaging' properties of stochastic approximation. Finally, it would be interesting to develop Lyapunov-type assumptions for stability of stochastic algorithms with set-valued mean fields.

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