

## LIMIT THEOREMS FOR SHIFT SELFSIMILAR ADDITIVE RANDOM SEQUENCES

TOSHIRO WATANABE

(Received November 15, 2000)

### 1. Introduction

We introduce shift selfsimilar random sequences, as a discrete time analogue of semi-selfsimilar processes. They are also extensions of stationary random sequences. We study limit theorems for those sequences having independent increments. Our results will be a potential resource for studying Galton-Watson branching trees and diffusions on fractals. Let  $\mathbf{R}^d$  be the  $d$ -dimensional Euclidean space and let  $\mathbf{Z} = \{0, \pm 1, \pm 2, \dots\}$ ,  $\mathbf{Z}_+ = \{0, 1, 2, \dots\}$  and  $\mathbf{N} = \{1, 2, \dots\}$ . We consider  $\mathbf{R}^d$  as the totality of  $d$ -dimensional column vectors and  $|\cdot|$  denotes the Euclidean norm in  $\mathbf{R}^d$ . In this paper, we use the words “increase” and “decrease” in the wide sense allowing flatness.

DEFINITION 1.1. An  $\mathbf{R}^d$ -valued random sequence  $\{X(n), n \in \mathbf{Z}\}$  is said to be *shift  $a$ -selfsimilar* if there exists a non-zero real number  $a$  such that

$$(1.1) \quad \{X(n+1), n \in \mathbf{Z}\} \stackrel{d}{=} \{aX(n), n \in \mathbf{Z}\},$$

where  $\stackrel{d}{=}$  denotes the equality in finite-dimensional distributions.

Let  $\{X(n), n \in \mathbf{Z}\}$  be a shift  $a$ -selfsimilar random sequence. Then we see that, for positive integer  $m$ , the distribution of  $X(mn)$  is the same as that of  $a^{n(m-1)}X(n)$ . Thus the shift selfsimilar random sequence is not selfsimilar in the usual sense.

An  $\mathbf{R}^d$ -valued stochastic process  $\{Y(t), t \geq 0\}$  is said to be *semi-selfsimilar* if there exist  $c \in (0, 1) \cup (1, \infty)$  and  $a > 0$  such that

$$(1.2) \quad \{Y(ct), t \geq 0\} \stackrel{d}{=} \{aY(t), t \geq 0\}.$$

Strictly semi-stable Lévy processes in  $\mathbf{R}^d$  and a Brownian motion on the unbounded Sierpinski gasket are important examples of semi-selfsimilar stochastic processes. If  $\{Y(t), t \geq 0\}$  is semi-selfsimilar, then the random sequence  $\{X(n), n \in \mathbf{Z}\}$  defined by  $X(n) = Y(c^n t_0)$  is shift  $a$ -selfsimilar for every  $t_0 > 0$ . We extend the property (1.1) to an operator version as follows.

DEFINITION 1.2. Let  $A$  be a real invertible  $d \times d$  matrix. An  $\mathbf{R}^d$ -valued random sequence  $\{X(n), n \in \mathbf{Z}\}$  is called *shift  $A$ -selfsimilar* if

$$(1.3) \quad \{X(n+1), n \in \mathbf{Z}\} \stackrel{d}{=} \{AX(n), n \in \mathbf{Z}\}.$$

DEFINITION 1.3. An  $\mathbf{R}^d$ -valued random sequence  $\{X(n), n \in \mathbf{Z}\}$  is said to have independent increments if, for every  $n \in \mathbf{Z}$ ,  $\{X(k), k \leq n\}$  and  $X(n+1) - X(n)$  are independent. It is equivalent to the condition that, for every  $n \in \mathbf{Z}$ ,  $X(n)$ ,  $X(n+1) - X(n)$ ,  $X(n+2) - X(n+1), \dots$  are independent. It is called to have independent increments in the weak sense if  $X(n+1) - X(n)$ ,  $n \in \mathbf{Z}$ , are independent. A random sequence with independent increments is also called an *additive* random sequence.

After this, we investigate for shift  $A$ -selfsimilar additive random sequences several problems which have already been studied for selfsimilar (or semi-selfsimilar) processes with independent increments. As to the latter processes, general results are written in [26], problems of recurrence and transience are discussed in [27], [36] and [37] although any criterion to classify recurrence and transience is not yet known, and problems on the rate of growth in increasing case are studied in [25] and [31] in comparison with the results for subordinators in [6] and [7].

The contents of this paper are the following. In Section 2 we give a characterization for non-degenerate shift  $A$ -selfsimilar additive random sequences. See Theorem 2.2. In Section 3 we prove that non-degenerate shift  $A$ -selfsimilar additive random sequences are transient if and only if  $A$  has an eigenvalue whose absolute value is greater than 1. See Corollary 3.2. Next we discuss in detail the rate of growth of shift  $a$ -selfsimilar additive random sequences in the “liminf” case for increasing sequences in Section 4, and in the “limsup” case for general sequences in Section 5 as follows. Let  $a > 1$ ,  $\mathcal{G}_0 = \{g(x) : g(x) \text{ is positive and decreasing on } [0, \infty)\}$  and  $\mathcal{G}_1 = \{g(x) : g(x) \text{ is positive and increasing on } [0, \infty)\}$ . Suppose that  $\{X(n), n \in \mathbf{Z}\}$  is an increasing shift  $a$ -selfsimilar additive random sequence in (1.4) and that it is an  $\mathbf{R}^d$ -valued non-zero shift  $a$ -selfsimilar additive random sequence in (1.5) below. We first prove that, for every  $g_0 \in \mathcal{G}_0$  and  $g_1 \in \mathcal{G}_1$ , there exist  $c_0$  and  $c_1 \in [0, \infty]$  such that

$$(1.4) \quad \liminf_{n \rightarrow \pm\infty} \frac{X(n)}{a^n g_0(|n|)} = c_0 \quad \text{a.s.}$$

and

$$(1.5) \quad \limsup_{n \rightarrow \pm\infty} \frac{|X(n)|}{a^n g_1(|n|)} = c_1 \quad \text{a.s.}$$

Here the abbreviation “a.s.” means “almost surely”. Then we obtain a necessary and sufficient condition for the existence of  $g_0 \in \mathcal{G}_0$  such that (1.4) holds for  $c_0 = 1$ . In the

case where there does not exist  $g_0 \in \mathcal{G}_0$  such that (1.4) holds for  $c_0 = 1$ , we give a criterion which classifies  $g_0 \in \mathcal{G}_0$  with  $c_0 = 0$  or  $g_0 \in \mathcal{G}_0$  with  $c_0 = \infty$  in (1.4). Further, changing the roles of  $g_0 \in \mathcal{G}_0$  and  $\{X(n), n \in \mathbf{Z}\}$ , we fix  $a > 1$  and  $g_0 \in \mathcal{G}_0$  then consider the family of the sequences  $\{X(n), n \in \mathbf{Z}\}$  which satisfy (1.4). We obtain a necessary and sufficient condition for the existence of  $\{X(n), n \in \mathbf{Z}\}$  such that (1.4) holds for  $c_0 = 1$ . In the case where there does not exist  $\{X(n), n \in \mathbf{Z}\}$  such that (1.4) holds for  $c_0 = 1$ , we give a criterion which classifies  $\{X(n), n \in \mathbf{Z}\}$  with  $c_0 = 0$  or  $\{X(n), n \in \mathbf{Z}\}$  with  $c_0 = \infty$  in (1.4). Moreover we get all of the above results replacing  $g_0 \in \mathcal{G}_0$ ,  $c_0$  and (1.4) by  $g_1 \in \mathcal{G}_1$ ,  $c_1$  and (1.5), respectively. Finally we give in Section 6 some examples of the results in Sections 4 and 5. The main results are as follows. The distribution of  $X(0) - X(-1)$  is denoted by  $\rho_1$ . The Laplace transform of a probability distribution  $\mu$  on  $[0, \infty)$  is denoted by  $L_\mu(t)$  for  $t \geq 0$ , that is,  $L_\mu(t) = \int_{[0, \infty)} e^{-tx} \mu(dx)$ .

**Theorem 4.2.** *There exists  $g(x) \in \mathcal{G}_0$  satisfying (1.4) with  $c_0 = 1$  if and only if  $\rho_1(\{0\}) = 0$ .*

**Corollary 4.2.** *Let  $g(x) \in \mathcal{G}_0$ . Suppose that  $\lambda := \rho_1(\{0\}) > 0$ . If*

$$\int_0^\infty K_\lambda \left( \frac{1}{g(x)} \right) dx = \infty \quad (\text{resp. } < \infty),$$

then

$$\liminf_{n \rightarrow \pm\infty} \frac{X(n)}{a^n g(|n|)} = 0 \quad (\text{resp. } = \infty) \quad \text{a.s.}$$

where  $K_\lambda(x)$  is regularly varying with index  $\log \lambda / \log a$  and defined on  $(0, \infty)$  as

$$K_\lambda(x) = x^{\log \lambda / \log a} \exp \left( \int_1^x \frac{\log L_{\rho_1}(u) - \log \lambda}{u \log a} du \right).$$

**Theorem 4.3.** *Let  $g(x) \in \mathcal{G}_0$ . There exists  $\{X(n), n \in \mathbf{Z}\}$  satisfying (1.4) with  $c_0 = 1$  if and only if*

$$\liminf_{x \rightarrow \infty} \frac{-\log g(x)}{\log x} = 0.$$

**Corollary 4.3.** *Let  $g(x) \in \mathcal{G}_0$ . Suppose that  $\rho_1(\{0\}) = 0$  and*

$$\liminf_{x \rightarrow \infty} \frac{-\log g(x)}{\log x} > 0.$$

Then we have

$$\liminf_{n \rightarrow \pm\infty} \frac{X(n)}{a^n g(|n|)} = \infty \quad \text{a.s.}$$

Define a function  $\rho_1^*(x)$  on  $[0, \infty)$  as  $\rho_1^*(x) = P(|X(0) - X(-1)| > x)$ . A positive measurable function  $f(t)$  on  $(0, \infty)$  is said to belong to the class *OR* if, for every  $\delta > 1$ ,  $\limsup_{t \rightarrow \infty} f(\delta t)/f(t) < \infty$  and  $\liminf_{t \rightarrow \infty} f(\delta t)/f(t) > 0$ . Define the inverse function  $g^{-1}(x)$  on  $[0, \infty)$  of  $g(x) \in \mathcal{G}_1$  as

$$g^{-1}(x) = \sup\{y \geq 0 : g(y) < x\}$$

with understanding that  $\sup \emptyset = 0$ .

**Theorem 5.2.** *There exists  $g(x) \in \mathcal{G}_1$  satisfying (1.5) with  $c_1 = 1$  if and only if  $\rho_1^*(x) \notin OR$ .*

**Corollary 5.1.** *Let  $g(x) \in \mathcal{G}_1$ . Suppose that  $\rho_1^*(x) \in OR$ . If*

$$\int_0^\infty \rho_1^*(g(x)) dx < \infty \quad (\text{resp. } = \infty),$$

then

$$\limsup_{n \rightarrow \pm\infty} \frac{|X(n)|}{a^n g(|n|)} = 0 \quad (\text{resp. } = \infty) \quad \text{a.s.}$$

**Theorem 5.3.** *Let  $g(x) \in \mathcal{G}_1$ . There exists  $\{X(n), n \in \mathbf{Z}\}$  satisfying (1.5) with  $c_1 = 1$  if and only if  $g^{-1}(x) + \log(1+x) \notin OR$ .*

**Corollary 5.2.** *Let  $g(x) \in \mathcal{G}_1$ . Suppose that  $g^{-1}(x) + \log(1+x) \in OR$ . If*

$$\int_{\mathbf{R}^d} g^{-1}(|x|) \rho_1(dx) < \infty \quad (\text{resp. } = \infty),$$

then

$$\limsup_{n \rightarrow \pm\infty} \frac{|X(n)|}{a^n g(|n|)} = 0 \quad (\text{resp. } = \infty) \quad \text{a.s.}$$

**REMARK 1.1.** Let  $g(x) \in \mathcal{G}_1$ . Then  $g^{-1}(x) + \log(1+x) \notin OR$  provided that

$$\liminf_{x \rightarrow \infty} \frac{\log g(x)}{\log x} = 0.$$

For every shift  $A$ -selfsimilar random sequence  $\{X(n), n \in \mathbf{Z}\}$ , the sequence  $\{S(n), n \in \mathbf{Z}\}$  defined by  $S(n) = A^{-n}X(n)$  is a stationary random sequence. Obviously the converse relation is also true. While shift  $A$ -selfsimilar random sequences have independent increments in some cases, stationary random sequences cannot have independent increments except in the trivial case. Thus the sequence  $\{S(n), n \in \mathbf{Z}\}$  cannot

inherit the independence of increments from the sequence  $\{X(n), n \in \mathbf{Z}\}$  through the above correspondence.

For every semi-selfsimilar process  $\{Y(t), t \geq 0\}$  with independent increments satisfying (1.2) with  $c > 1$ , the sequence  $\{X(n), n \in \mathbf{Z}\}$  defined by  $X(n) = Y(c^n)$  is a shift  $a$ -selfsimilar additive random sequence. This example shows the existence of a rich class of shift  $a$ -selfsimilar additive random sequences, but it is formal. A non-formal interesting example of a shift selfsimilar additive random sequence is found in the hitting time sequence for the Brownian motion  $\{B(t), t \geq 0\}$  starting at the origin on the unbounded Sierpinski gasket  $\widehat{G}$  in  $\mathbf{R}^2$  as below. Define the sets  $F_n$  in  $\widehat{G}$  as  $F_n = \{x \in \widehat{G} : |x| = 2^n\}$  for  $n \in \mathbf{Z}$  and let  $T_n$  be the first hitting time of the set  $F_n$  for the process  $\{B(t), t \geq 0\}$ , that is,  $T_n = \inf\{t > 0 : B(t) \in F_n\}$ . Then  $\{T_n, n \in \mathbf{Z}\}$  is an increasing shift 5-selfsimilar additive random sequence. The sequence  $\{T_n, n \in \mathbf{Z}\}$  plays a key role in the theory of the Brownian motion  $\{B(t), t \geq 0\}$  on  $\widehat{G}$ . See [1]. Our results will be applied in a forthcoming paper [34] to this example and its extensions which are associated with supercritical branching processes. In particular, we shall give an estimate of the unknown constants in two types of laws of the iterated logarithm for the process  $\{B(t), t \geq 0\}$  on  $\widehat{G}$ . Moreover those studies will be the first step to consider the exact Hausdorff and packing measures for the boundary of a Galton-Watson branching tree, which are discussed in [9], [14] and [15].

Selfsimilar processes were introduced in [13] under the name of semi-stable processes. Some extensions in operator versions are found in [12] and then [10]. The meaning of selfsimilarity in the theory of stochastic processes is stronger than that in the theory of selfsimilar sets and measures which were introduced in [11]. Thus Maejima and Sato introduced in [18] the notion of semi-selfsimilarity in stochastic processes. They proved that the marginal distributions of stochastically continuous semi-selfsimilar processes  $\{Y(t), t \geq 0\}$  with independent increments are semi-selfdecomposable in the sense introduced in [17] and conversely any semi-selfdecomposable distribution can be the distribution of  $Y(1)$  for some (not necessarily unique in law)  $\{Y(t), t \geq 0\}$ . While the marginal distributions of stochastically continuous semi-selfsimilar processes are infinitely divisible, those of shift  $A$ -selfsimilar additive random sequences are not necessarily infinitely divisible. We show, in Theorem 2.1, that in the case where  $A$  is a real invertible  $d \times d$  matrix all of whose eigenvalues have absolute values greater than 1, the marginal distributions of shift  $A$ -selfsimilar additive random sequences  $\{X(n), n \in \mathbf{Z}\}$  are  $A^{-1}$ -decomposable in the sense of [16] and [35] and conversely any  $A^{-1}$ -decomposable distribution can be the distribution of  $X(0)$  for some (not necessarily unique in law) shift  $A$ -selfsimilar additive random sequence  $\{X(n), n \in \mathbf{Z}\}$ . In this way we can have random sequences of this kind on selfsimilar sets such as the Cantor sets and the Sierpinski gasket. They cannot be expressed as  $\{Y(c^n), n \in \mathbf{Z}\}$  for any stochastically continuous semi-selfsimilar processes  $\{Y(t), t \geq 0\}$  with independent increments satisfying (1.2) with  $c > 1$ . See Example 6.1.

We finish this section by mentioning that, since shift  $a$ -selfsimilar additive random sequences with  $a > 1$  are considered as sums of independent and shift  $a$ -selfsimilarly distributed random variables, it is of interest to compare our results with those on random walks. See, for recurrence and transience, [5], [20], [29] and [30], and, for the rate of growth, [22], [23] and [24].

## 2. Characterization

Denote by  $\langle z, x \rangle$  and  $|x|$  the Euclidean inner product of  $z$  and  $x$  and the Euclidean norm of  $x$  in  $\mathbf{R}^d$ , respectively. Denote by  $A'$  the transpose of a real matrix  $A$  and by  $\|Q\|$  the operator norm of a real  $d \times d$  matrix  $Q$  on  $\mathbf{R}^d$ , that is,  $\|Q\| = \sup_{|x|=1} |Qx|$ . The symbol  $\delta_a(dx)$  stands for the probability distribution on  $\mathbf{R}^d$  concentrated at  $a \in \mathbf{R}^d$ . Let  $\widehat{\mu}(z)$  and  $S_\mu$  be the characteristic function and the support of a probability distribution  $\mu$  on  $\mathbf{R}^d$ , respectively. We denote by  $\bar{\mu}$  the reflection of  $\mu$ , that is,  $\bar{\mu}(E) = \mu(-E)$  for Borel sets  $E$  in  $\mathbf{R}^d$ . Denote by  $\mu * \rho$  the convolution of probability distributions  $\mu$  and  $\rho$  on  $\mathbf{R}^d$ . Let  $B$  be a real invertible  $d \times d$  matrix all of whose eigenvalues have absolute values less than 1. A probability distribution  $\mu$  on  $\mathbf{R}^d$  is said to be  $B$ -decomposable if there exists a probability distribution  $\rho$  on  $\mathbf{R}^d$  such that

$$(2.1) \quad \widehat{\mu}(z) = \widehat{\mu}(B'z)\widehat{\rho}(z).$$

Note that  $B$ -decomposable distributions are not necessarily infinitely divisible. A probability distribution  $\mu$  on  $\mathbf{R}^d$  is  $B$ -decomposable if and only if there exists a probability distribution  $\rho$  on  $\mathbf{R}^d$  such that

$$(2.2) \quad \int_{\mathbf{R}^d} \log(1 + |x|)\rho(dx) < \infty$$

and

$$(2.3) \quad \widehat{\mu}(z) = \prod_{n=0}^{\infty} \widehat{\rho}(B'^n z).$$

Any distribution  $\rho$  in (2.1) can be used as the distribution  $\rho$  in (2.2) and (2.3). Thus a  $B$ -decomposable distribution  $\mu$  on  $\mathbf{R}^d$  is determined by  $\rho$  in (2.1) but  $\rho$  is not necessarily determined by  $\mu$ . In the case where  $S_\mu \subset [0, \infty)^d$ ,  $\rho$  is uniquely determined by  $\mu$ . The class of all  $B$ -decomposable distributions is rather broad and contains many important limit distributions such as operator semi-stable distributions and selfsimilar measures. See [4], [19] and [32]. Since  $B^2$  is expressed as  $e^Q$  with  $Q$  being a real  $d \times d$  matrix all of whose eigenvalues have negative real parts,  $B$ -decomposable distributions are always  $e^Q$ -decomposable. A probability distribution  $\mu$  on  $\mathbf{R}^d$  is said to be full if  $S_\mu$  is not contained in any proper hyperplane in  $\mathbf{R}^d$ . Wolfe showed in [35] that every full  $e^Q$ -decomposable distribution is either continuous singular or

absolutely continuous. Continuity properties of  $e^Q$ -decomposable distributions are studied in [32] and [33]. An  $\mathbf{R}^d$ -valued random sequence  $\{Y(n), n \in \mathbf{Z}\}$  on a probability space  $(\Omega, \mathcal{F}, P)$  is called a zero sequence if  $P(Y(n) = 0 \text{ for } n \in \mathbf{Z}) = 1$ . It is called deterministic if there exists a non-random sequence  $a_n \in \mathbf{R}^d$  such that  $P(Y(n) = a_n \text{ for } n \in \mathbf{Z}) = 1$ . It is called non-degenerate if the distributions of  $Y(n)$  are full for all  $n \in \mathbf{Z}$ .

From now on, let  $\{X(n), n \in \mathbf{Z}\}$  be an  $\mathbf{R}^d$ -valued shift  $A$ -selfsimilar random sequence with independent increments in the weak sense on a probability space  $(\Omega, \mathcal{F}, P)$ . Denote by  $\mu_n$  and  $\rho_l$  the distribution of  $X(n)$  for  $n \in \mathbf{Z}$  and that of  $X(0) - X(-l)$  for  $l \in \mathbf{N}$ , respectively.

**Theorem 2.1.** *Let  $A$  be a real invertible  $d \times d$  matrix all of whose eigenvalues have absolute values greater than 1 and let  $B = A^{-1}$ .*

(i) *Let  $\{X(n), n \in \mathbf{Z}\}$  be an  $\mathbf{R}^d$ -valued shift  $A$ -selfsimilar random sequence with independent increments in the weak sense. The probability distribution  $\rho_1$  satisfies that*

$$(2.4) \quad \int_{\mathbf{R}^d} \log(1 + |x|) \rho_1(dx) < \infty.$$

*The distributions  $\mu_n$  are  $B$ -decomposable and their characteristic functions are represented as*

$$(2.5) \quad \widehat{\mu}_n(z) = \prod_{k=0}^{\infty} \widehat{\rho}_1((B')^{k-n}z).$$

*Moreover,  $\{X(n), n \in \mathbf{Z}\}$  has independent increments and*

$$\lim_{n \rightarrow -\infty} X(n) = 0 \quad \text{a.s.}$$

(ii) *Conversely, if a probability distribution  $\rho$  satisfying (2.2) is given, then there is a unique (in law) shift  $A$ -selfsimilar additive random sequence  $\{X(n), n \in \mathbf{Z}\}$  satisfying  $\rho_1 = \rho$ . That is, for every  $B$ -decomposable distribution  $\mu$  on  $\mathbf{R}^d$ , there is a (not necessarily unique in law) shift  $A$ -selfsimilar additive random sequence  $\{X(n), n \in \mathbf{Z}\}$  satisfying  $\mu_0 = \mu$ .*

**Proof.** We see from the shift  $A$ -selfsimilarity that

$$\widehat{\mu}_n(z) = \widehat{\mu}_0((B')^{-n}z).$$

Since  $(B')^n \rightarrow O$  as  $n \rightarrow \infty$ , we have  $\lim_{n \rightarrow -\infty} \widehat{\mu}_n(z) = 1$  for any  $z \in \mathbf{R}^d$ . Thus  $\mu_n$  converges weakly to  $\delta_0(dx)$  as  $n \rightarrow -\infty$ . Hence  $X(-n)$  converges in probability to 0 as  $n \rightarrow \infty$ . Therefore, there are  $n_k \uparrow \infty$  such that

$$(2.6) \quad \lim_{k \rightarrow \infty} X(-n_k) = 0 \quad \text{a.s.}$$

Thus we see from the independence of increments in the weak sense and the shift  $A$ -selfsimilarity that

$$\widehat{\mu}_0(z) = \lim_{n \rightarrow \infty} E \exp(i \langle z, X(0) - X(-n) \rangle) = \lim_{n \rightarrow \infty} \prod_{j=0}^{n-1} \widehat{\rho}_1((B')^j z).$$

We have in like manner

$$\widehat{\mu}_{-1}(z) = \lim_{n \rightarrow \infty} \prod_{j=1}^{n-1} \widehat{\rho}_1((B')^j z).$$

Hence we obtain that

$$\widehat{\mu}_0(z) = \widehat{\mu}_{-1}(z) \widehat{\rho}_1(z) = \widehat{\mu}_0(B'z) \widehat{\rho}_1(z),$$

that is,  $\mu_0$  is  $B$ -decomposable and  $\int_{\mathbf{R}^d} \log(1 + |x|) \rho_1(dx) < \infty$ . By the same way, we get that

$$\widehat{\mu}_n(z) = \widehat{\mu}_n(B'z) \widehat{\rho}_1((B')^{-n}z) = \prod_{k=0}^{\infty} \widehat{\rho}_1((B')^{k-n}z).$$

Therefore  $\mu_n$  are  $B$ -decomposable for  $n \in \mathbf{Z}$ . Thus we have proved the first assertion of (i). Taking a sufficiently large positive integer  $k$  satisfying  $\|B^k\| < 1$ , (see Lemma 2.6 of [25]) we have

$$\begin{aligned} & \sum_{n=0}^{\infty} P(|X(-n) - X(-n-1)| \geq \|B^k\|^{n/(2k)}) \\ & \leq \sum_{n=0}^{\infty} P(|X(0) - X(-1)| \geq c_1 \|B^k\|^{-n/(2k)}) \\ & \leq c_2 \int_{\mathbf{R}^d} \log(2 + |x|) \rho_1(dx) < \infty, \end{aligned}$$

where  $c_1$  and  $c_2$  are positive constants. Hence we see from the Borel-Cantelli lemma that  $\{X(-n)\}$  is a Cauchy sequence in  $\mathbf{R}^d$  as  $n \rightarrow \infty$  almost surely. Since we already showed in (2.6) that  $\lim_{k \rightarrow \infty} X(-n_k) = 0$  almost surely, we get  $\lim_{n \rightarrow -\infty} X(n) = 0$  almost surely. Hence it is evident that

$$X(n) = \sum_{k=0}^{\infty} (X(n-k) - X(n-k-1)) \quad \text{a.s.}$$

This shows that  $\{X(n), n \in \mathbf{Z}\}$  has independent increments. Next we prove the assertion (ii). Let  $Y(n), n \in \mathbf{Z}$ , be independent identically distributed  $\mathbf{R}^d$ -valued random variables with the distribution  $\rho$ . The sum  $\sum_{n=0}^{\infty} B^n Y(-n)$  is convergent almost



surely if and only if (2.2) holds. See [4] and [19]. Then the sequence  $\{X(n), n \in \mathbf{Z}\}$  defined by  $X(n) = \sum_{j=-\infty}^n A^j Y(j)$  is a shift  $A$ -self-similar additive random sequence with  $\rho_1 = \rho$ . Uniqueness is obviously true because all finite dimensional distributions of  $\{X(n), n \in \mathbf{Z}\}$  are determined by  $\rho_1$ .  $\square$

**REMARK 2.1.** Let  $A$  be a real invertible  $d \times d$  matrix all of whose eigenvalues have absolute values greater than 1 and let  $B = A^{-1}$ . Let  $\{X(n), n \in \mathbf{Z}\}$  be an  $\mathbf{R}^d$ -valued shift  $A$ -self-similar additive random sequence. We see from Theorem 2.1 that the distribution of  $\{X(n), n \in \mathbf{Z}\}$  is determined by  $\rho_1$ . Thus properties of  $\{X(n), n \in \mathbf{Z}\}$  should be characterized in terms of  $\rho_1$ . If  $\rho_1$  is a discrete probability distribution, then  $\mu_n$  are self-similar for  $n \in \mathbf{Z}$  in the following sense. Let  $N^*$  be a positive integer or  $N^* = \infty$ . Define a mapping  $T_a$  on  $\mathbf{R}^d$  as  $T_a x = Bx + a$  for  $a \in \mathbf{R}^d$ . Define a probability distribution  $T_a \mu$  on  $\mathbf{R}^d$  for a probability distribution  $\mu$  on  $\mathbf{R}^d$  as  $T_a \mu(E) = \mu(T_a^{-1} E)$  for Borel sets  $E$  in  $\mathbf{R}^d$ . If  $\rho_1(dx) = \sum_{j=1}^{N^*} p_j \delta_{a_j}(dx)$  for  $a_j \in \mathbf{R}^d$  and for  $p_j \geq 0$  with  $\sum_{j=1}^{N^*} p_j = 1$ , then  $\mu_n = \sum_{j=1}^{N^*} p_j T_{B^{-n} a_j} \mu_n$  for  $n \in \mathbf{Z}$ . This self-similarity of probability measures is slightly different from the original one introduced in [11]. A relationship between the upper Hausdorff dimension of  $\mu_0$  and the entropy of  $\rho_1$  is discussed in [33].

The following lemma is well known. See Lemma 13.9 of [26].

**Lemma 2.1.** *Let  $\mu$  be a probability distribution on  $\mathbf{R}^d$ . If  $|\widehat{\mu}(z)| = 1$  on a neighborhood of  $z = 0$ , then  $\mu(dx) = \delta_a(dx)$  for some  $a \in \mathbf{R}^d$ .*

Let  $G$  be a real invertible  $d \times d$  matrix and let  $m(x)$  be its minimal polynomial. Assume that  $m(x) = \prod_{j=1}^k \{m_j(x)\}^{r_j}$ , where  $m_j(x)$  are distinct irreducible monic polynomials over  $\mathbf{R}^1$  and  $r_j$  are positive integers. Each polynomial  $m_j(x)$  has a unique real zero  $\alpha_j$  or has two non-real zeros  $\alpha_j$  and  $\bar{\alpha}_j$ , where  $\bar{\alpha}_j$  is the complex conjugate of  $\alpha_j$ . Let  $W_j = \ker(\{m_j(G)\}^{r_j})$  and  $W'_j = \ker(\{m_j(G')\}^{r_j})$  for  $1 \leq j \leq k$ . Then  $W_j$  are  $G$ -invariant and  $W'_j$  are  $G'$ -invariant. We have direct sum decompositions

$$\mathbf{R}^d = W_1 \oplus W_2 \oplus \cdots \oplus W_k$$

and

$$\mathbf{R}^d = W'_1 \oplus W'_2 \oplus \cdots \oplus W'_k.$$

**Lemma 2.2.** *Let  $G$  be a real invertible  $d \times d$  matrix. Let  $\zeta$  be a full probability distribution on  $\mathbf{R}^d$ . Suppose that there exists a probability distribution  $\eta$  on  $\mathbf{R}^d$  such that*

$$(2.7) \quad \widehat{\zeta}(z) = \widehat{\zeta}(G'z)\widehat{\eta}(z).$$

Then the following statements are true.

- (i) All eigenvalues of  $G$  have absolute values less than or equal to 1. Those with absolute value 1 are simple zeros of the minimal polynomial of  $G$ .
- (ii) Let  $V_1$  be the direct sum of all  $W_j$  satisfying  $|\alpha_j| < 1$  and let  $V_2$  be the direct sum of all  $W_j$  satisfying  $|\alpha_j| = 1$ . Let  $T_l$  be the projector to  $V_l$  for  $l = 1, 2$  in the direct sum decomposition  $\mathbf{R}^d = V_1 \oplus V_2$ . Define probability distributions  $\zeta_l$  and  $\eta_l$  on  $\mathbf{R}^d$  for  $l = 1, 2$  as  $\zeta_l(E) = \zeta(T_l^{-1}(E \cap V_l))$  and  $\eta_l(E) = \eta(T_l^{-1}(E \cap V_l))$  for Borel sets  $E$  in  $\mathbf{R}^d$ . Then we have

$$(2.8) \quad \widehat{\zeta}(z) = \widehat{\zeta}_1(z)\widehat{\zeta}_2(z) \quad \text{and} \quad \widehat{\zeta}_l(z) = \widehat{\zeta}_l(G'z)\widehat{\eta}_l(z) \quad \text{for } l = 1, 2$$

with  $\int_{V_1} \log(1 + |x|)\eta_1(dx) < \infty$  and  $\eta_2(dx) = \delta_a(dx)$  for some  $a \in V_2$ .

Proof. Let  $\text{Leb}(dx)$  be the Lebesgue measure on  $\mathbf{R}^d$ . By considering the Jordan canonical form of the matrix  $G$ , we have

$$\left\{x \in \mathbf{R}^d : \liminf_{n \rightarrow \infty} |G^n x| < \infty\right\} = \left\{x \in \mathbf{R}^d : \limsup_{n \rightarrow \infty} |G^n x| < \infty\right\}.$$

Denote the above set by  $H$ . Note that  $H$  is a subspace in  $\mathbf{R}^d$ . Denote the closed ball with radius  $r$  and the center 0 by  $B_r$ . For any  $\delta > 0$ , we can take sufficiently small  $r > 0$  such that  $|\widehat{\zeta}(z)|^2 \geq 1 - \delta$  for  $z \in B_r$ . We see from the Riemann-Lebesgue theorem that

$$\lim_{n \rightarrow \infty} \int_{B_r} \cos\langle z, G^n x \rangle dz = 0 \quad \text{for } x \in H^c.$$

Note from (2.7) that

$$|\widehat{\zeta}(z)| \leq |\widehat{\zeta}((G')^n z)| \quad \text{for } n \in \mathbf{Z}_+.$$

Hence we obtain that

$$\begin{aligned} (1 - \delta)\text{Leb}(B_r) &\leq \int_{B_r} |\widehat{\zeta}(z)|^2 dz \\ &\leq \limsup_{n \rightarrow \infty} \int_{\mathbf{R}^d} \zeta * \bar{\zeta}(dx) \int_{B_r} \cos\langle z, G^n x \rangle dz \\ &\leq \zeta * \bar{\zeta}(H)\text{Leb}(B_r). \end{aligned}$$

It follows that  $\zeta * \bar{\zeta}(H) = 1$ , that is,  $H = \mathbf{R}^d$  by the fullness of  $\zeta$ . Hence the assertion (i) is true. Next we prove the assertion (ii). We define  $V'_l$  for  $l = 1, 2$  by replacing  $W_j$  with  $W'_j$  in the definition of  $V_l$ . We see from (2.7) that

$$\widehat{\zeta}_l(z) = \widehat{\zeta}_l(G'z)\widehat{\eta}_l(z) \quad \text{for } l = 1, 2.$$

Let  $G_l$  be the restriction of  $G$  to  $V_l$  and let  $I_l$  be the identity operator on  $V_l$ . We see that  $\zeta_1$  is  $B$ -decomposable on  $V_1$  with  $B = G_1$  and hence  $\int_{V_1} \log(1 + |x|) \eta_1(dx) < \infty$ . Since  $(G'_2)^n$ ,  $n \in \mathbf{Z}_+$ , are relatively compact in operator norm on  $V'_2$ , there is a sequence  $m_k$  of integers such that  $m_{k+1} - m_k \uparrow \infty$  and  $(G'_2)^{m_k}$  converges to some operator  $G'_0$  in the operator norm on  $V'_2$  as  $k \rightarrow \infty$ . Note that the absolute values of all eigenvalues of  $G'_0$  are 1 and hence  $G'_0$  is invertible on  $V'_2$ . Thus there is a sequence  $n_k := m_{k+1} - m_k \uparrow \infty$  of integers such that  $(G'_2)^{n_k} \rightarrow I'_2$  in operator norm on  $V'_2$  as  $k \rightarrow \infty$ . Hence we obtain that

$$|\widehat{\zeta}_2(z)| = \lim_{k \rightarrow \infty} |\widehat{\zeta}_2((G'_2)^{n_k} z)| \prod_{j=0}^{n_k-1} |\widehat{\eta}_2((G'_2)^j z)| \leq |\widehat{\zeta}_2(z)| |\widehat{\eta}_2(z)| \quad \text{for } z \in V'_2.$$

Noting that  $|\widehat{\zeta}_2(z)| > 0$  on  $V'_2 \cap B_r$  for sufficiently small  $r > 0$ , we find that  $|\widehat{\eta}_2(z)| = 1$  on  $V'_2 \cap B_r$  and hence, by Lemma 2.1,  $\eta_2(dx) = \delta_a(dx)$  for some  $a \in V_2$ . Define probability distributions  $\sigma_k$  on  $\mathbf{R}^d$  as  $\widehat{\sigma}_k(z) = \prod_{j=0}^{n_k-1} \widehat{\eta}((G')^j z)$ . We obtain from (2.7) that

$$\widehat{\zeta}(z) = \widehat{\zeta}((G')^{n_k} z) \widehat{\sigma}_k(z).$$

Since  $(G')^{n_k} z \rightarrow T'_2 z$  as  $k \rightarrow \infty$ , we have

$$\lim_{k \rightarrow \infty} \widehat{\zeta}((G')^{n_k} z) = \widehat{\zeta}_2(z).$$

Taking a subsequence, if necessary, we see from Lemma of [16] or Theorem 2.1 of [21] that  $\sigma_k$  converges weakly to a probability measure  $\nu$  on  $\mathbf{R}^d$  as  $k \rightarrow \infty$ . It follows that

$$(2.9) \quad \widehat{\zeta}(z) = \lim_{k \rightarrow \infty} \widehat{\zeta}((G')^{n_k} z) \widehat{\sigma}_k(z) = \widehat{\zeta}_2(z) \widehat{\nu}(z).$$

We have  $\widehat{\zeta}_2(T'_1 z) = \widehat{\zeta}_2(0) = 1$  for  $z \in \mathbf{R}^d$  and hence by (2.9)

$$\widehat{\nu}(T'_1 z) = \frac{\widehat{\zeta}(T'_1 z)}{\widehat{\zeta}_2(T'_1 z)} = \widehat{\zeta}_1(z) \quad \text{for } z \in \mathbf{R}^d.$$

On the other hand, we get by (2.9) that, for some small  $r > 0$ ,

$$\widehat{\nu}(T'_2 z) = \frac{\widehat{\zeta}(T'_2 z)}{\widehat{\zeta}_2(z)} = 1 \quad \text{for } z \in B_r,$$

and hence  $S_\nu \subset V_1$ . It follows that  $\widehat{\nu}(z) = \widehat{\nu}(T'_1 z) = \widehat{\zeta}_1(z)$ , that is,  $\nu = \zeta_1$ . Thus we have by (2.9)

$$\widehat{\zeta}(z) = \widehat{\zeta}_1(z) \widehat{\zeta}_2(z).$$

The proof of the lemma is complete.  $\square$

Next we intend to characterize shift  $A$ -selfsimilar additive random sequences. However, since it is difficult to treat the general case, we discuss only the non-degenerate case.

**Theorem 2.2.** *Let  $A$  be a real invertible  $d \times d$  matrix. Let  $\{X(n), n \in \mathbf{Z}\}$  be an  $\mathbf{R}^d$ -valued non-degenerate shift  $A$ -selfsimilar additive random sequence. Then the following statements are true.*

- (i) *All eigenvalues of  $A$  have absolute values greater than or equal to 1. Those with absolute value 1 are simple zeros of the minimal polynomial of  $A$ .*
- (ii) *There is a direct sum decomposition  $\mathbf{R}^d = V_1 \oplus V_2$  such that  $V_1$  and  $V_2$  are  $A$ -invariant, all eigenvalues of  $A$  on  $V_1$  have absolute values greater than 1, and those on  $V_2$  have absolute value 1. Let  $A_l$  be the restriction of  $A$  to  $V_l$  for  $l = 1, 2$ . Then  $\{X(n), n \in \mathbf{Z}\}$  is decomposed as the sum of two independent random sequences  $\{X_l(n), n \in \mathbf{Z}\}$ ,  $l = 1, 2$ , such that, for each  $l$ ,  $\{X_l(n), n \in \mathbf{Z}\}$  is a shift  $A_l$ -selfsimilar additive random sequence on  $V_l$ , and almost surely  $\{X_2(n), n \in \mathbf{Z}\}$  has deterministic increments and almost surely  $\sup_{n \in \mathbf{Z}} |X_2(n)| < \infty$ .*

*Proof.* We see from the shift  $A$ -selfsimilarity and the independence of increments that

$$\widehat{\mu}_0(z) = \widehat{\mu}_0((A^{-1})'z)\widehat{\rho}_1(z).$$

By setting  $G = A^{-1}$ ,  $\zeta = \mu_0$ , and  $\eta = \rho_1$ , we can use Lemma 2.2 and hence the assertion (i) is true. Define  $\{X_l(n), n \in \mathbf{Z}\}$  by  $X_l(n) = T_l X(n)$  for  $l = 1, 2$ . Then obviously  $X(n) = X_1(n) + X_2(n)$ , and  $\{X_l(n), n \in \mathbf{Z}\}$  are shift  $A_l$ -selfsimilar additive random sequences on  $V_l$  for  $l = 1, 2$ . We see from (ii) of Lemma 2.2 that the distribution of  $X_2(0) - X_2(-1)$  is a delta distribution  $\delta_a$  with  $a \in V_2$  and hence  $\{X_2(n), n \in \mathbf{Z}\}$  has deterministic increments almost surely. The fact that  $\sup_{n \in \mathbf{Z}} |X_2(n)| < \infty$  a.s. is clear from the fact that  $\sup_{n \in \mathbf{Z}_+} |\sum_{j=0}^n A^j a| < \infty$  and  $\sup_{n \in \mathbf{Z}_+} |\sum_{j=-n}^0 A^j a| < \infty$  because all eigenvalues of  $A$  on  $V_2$  have absolute value 1 and are simple zeros of the minimal polynomial of  $A$ . Finally we prove the independence of two random sequences  $\{X_l(n), n \in \mathbf{Z}\}$  for  $l = 1, 2$  by using (ii) of Lemma 2.2 and the independence of increments of  $\{X(n), n \in \mathbf{Z}\}$ . Let  $N$  be an arbitrary positive integer,  $z_l^{(1)}$ ,  $z_l^{(2)}$  be arbitrary in  $\mathbf{R}^d$  and define  $w_l = T_1' z_l^{(1)} + T_2' z_l^{(2)}$  for  $1 \leq l \leq N$ . Note that  $\langle z_l^{(1)}, X_1(n_l) \rangle = \langle w_l, X_1(n_l) \rangle$  and  $\langle z_l^{(2)}, X_2(n_l) \rangle = \langle w_l, X_2(n_l) \rangle$  for any  $n_l \in \mathbf{Z}$  with  $1 \leq l \leq N$ . We obtain from (2.8) and the properties of increments of  $\{X(n), n \in \mathbf{Z}\}$ ,  $\{X_1(n), n \in \mathbf{Z}\}$ , and  $\{X_2(n), n \in \mathbf{Z}\}$  that, for any strictly increasing sequence  $n_l \in \mathbf{Z}$

with  $0 \leq l \leq N$ ,

$$\begin{aligned}
 & E \exp \left( i \sum_{l=1}^N \left( \langle z_l^{(1)}, X_1(n_l) \rangle + \langle z_l^{(2)}, X_2(n_l) \rangle \right) \right) \\
 &= E \exp \left( i \sum_{l=1}^N \langle w_l, X(n_l) \rangle \right) \\
 &= \left[ \prod_{j=1}^N E \exp \left( i \sum_{l=j}^N \langle w_l, X(n_j) - X(n_{j-1}) \rangle \right) \right] E \exp \left( i \sum_{l=1}^N \langle w_l, X(n_0) \rangle \right) \\
 &= \prod_{k=1}^2 \left[ \prod_{j=1}^N E \exp \left( i \sum_{l=j}^N \langle w_l, X_k(n_j) - X_k(n_{j-1}) \rangle \right) \right] E \exp \left( i \sum_{l=1}^N \langle w_l, X_k(n_0) \rangle \right) \\
 &= E \exp \left( i \sum_{l=1}^N \langle w_l, X_1(n_l) \rangle \right) E \exp \left( i \sum_{l=1}^N \langle w_l, X_2(n_l) \rangle \right) \\
 &= E \exp \left( i \sum_{l=1}^N \langle z_l^{(1)}, X_1(n_l) \rangle \right) E \exp \left( i \sum_{l=1}^N \langle z_l^{(2)}, X_2(n_l) \rangle \right)
 \end{aligned}$$

Thus we have established the independence of  $\{X_1(n), n \in \mathbf{Z}\}$  and  $\{X_2(n), n \in \mathbf{Z}\}$ .  $\square$

### 3. Transience

An  $\mathbf{R}^d$ -valued random sequence  $\{Y(n), n \in \mathbf{Z}\}$  is said to be transient if  $P(\lim_{n \rightarrow \infty} |Y(n)| = \infty) = 1$ . In this section we prove the following theorem.

**Theorem 3.1.** *Let  $A$  be a real invertible  $d \times d$  matrix all of whose eigenvalues have absolute values greater than 1. Then all non-zero  $\mathbf{R}^d$ -valued shift  $A$ -selfsimilar additive random sequences  $\{X(n), n \in \mathbf{Z}\}$  are transient.*

**Corollary 3.1.** *Let  $\{Y(t), t \geq 0\}$  be an  $\mathbf{R}^d$ -valued stochastically continuous semi-selfsimilar process with independent increments satisfying (1.2) with  $c > 1$ . If  $P(Y(t_1) \neq 0) > 0$  for some  $t_1 > 0$ , then the random sequence  $\{Y(c^n t_0), n \in \mathbf{Z}\}$  is transient for every  $t_0 > 0$ .*

REMARK 3.1. In case  $\{Y(t), t \geq 0\}$  is a strictly stable Lévy process in  $\mathbf{R}^d$ , the corollary above is already shown in [3]. The assertion of the corollary remains true in the case where  $\{Y(t), t \geq 0\}$  is a strictly operator semi-stable Lévy process in  $\mathbf{R}^d$ .

We obtain the following corollary, combining Theorems 2.2 and 3.1.

**Corollary 3.2.** *Let  $A$  be a real invertible  $d \times d$  matrix. Non-degenerate  $\mathbf{R}^d$ -valued shift  $A$ -selfsimilar additive random sequences  $\{X(n), n \in \mathbf{Z}\}$  are transient if and only if  $A$  has an eigenvalue whose absolute value is greater than 1.*

**Lemma 3.1.** *Let  $\{Y(n), n \in \mathbf{Z}\}$  be an  $\mathbf{R}^d$ -valued random sequence. If*

$$\sum_{n=0}^{\infty} P(|Y(n)| \leq a) < \infty \quad \text{for } \forall a > 0,$$

*then  $\{Y(n), n \in \mathbf{Z}\}$  is transient.*

Proof. Proof is clear from the Borel-Cantelli lemma. □

**REMARK 3.2.** There exists a non-zero, non-transient shift  $A$ -selfsimilar random sequence. It is shown as follows. Let  $A$  be a real invertible  $d \times d$  matrix. Let  $\{Y(n), n \in \mathbf{Z}\}$  be an  $\mathbf{R}^d$ -valued shift  $A$ -selfsimilar random sequence such that  $Y(n), n \in \mathbf{Z}$ , are independent. Then it follows from the Borel-Cantelli lemma that  $\{Y(n), n \in \mathbf{Z}\}$  is transient if and only if

$$\sum_{n=0}^{\infty} P(|Y(n)| \leq a) < \infty \quad \text{for } \forall a > 0.$$

In the case where  $A$  is a real invertible  $d \times d$  matrix all of whose eigenvalues have absolute values greater than 1, it is equivalent from the shift  $A$ -selfsimilarity to  $E(-\log(|Y(0)| \wedge 1)) < \infty$ . Thus the first assertion is obviously true.

**Lemma 3.2.** *Let  $\{Y(n), n \in \mathbf{Z}\}$  be an  $\mathbf{R}^d$ -valued random sequence and let  $\eta_n$  be the distribution of  $Y(n)$  for  $n \in \mathbf{Z}$ . If there exists  $a_0 > 0$  such that*

$$(3.1) \quad \sum_{n=0}^{\infty} \int_{|z| \leq a_0} |\widehat{\eta}_n(z)| dz < \infty,$$

*then  $\{Y(n), n \in \mathbf{Z}\}$  is transient.*

Proof. Let  $x = (x_j)_{j=1}^d \in \mathbf{R}^d$ . Define a function  $f_a(x)$  on  $\mathbf{R}^d$  for  $a > 0$  as

$$f_a(x) = \prod_{j=1}^d \left( \frac{2 \sin(ax_j/2)}{ax_j} \right)^2$$

with understanding that  $(\sin 0)/0 = 1$ . Then the Fourier transform  $\widehat{f}_a(z)$  of  $f_a(x)$  is

given by

$$\begin{aligned} \widehat{f}_a(z) &= \int_{\mathbf{R}^d} \exp(i\langle z, x \rangle) f_a(x) dx \\ &= (2\pi a^{-1})^d \prod_{j=1}^d (1 - a^{-1}|z_j|) 1_{[-a,a]}(z_j), \end{aligned}$$

where  $1_{[-a,a]}(x)$  is the indicator function of the interval  $[-a, a]$ . We see from the Parseval's equality that

$$\begin{aligned} \sum_{n=0}^{\infty} E(f_a(Y(n))) &= (2\pi)^{-d} \sum_{n=0}^{\infty} \int_{\mathbf{R}^d} \widehat{\eta}_n(z) \widehat{f}_a(-z) dz \\ &\leq a^{-d} \sum_{n=0}^{\infty} \int_{|z| \leq \sqrt{d}a} |\widehat{\eta}_n(z)| dz. \end{aligned}$$

Hence we find that (3.1) implies that  $\sum_{n=0}^{\infty} E(f_a(Y(n))) < \infty$  for any  $a \in (0, a_0/\sqrt{d})$ . Thus the lemma follows from Lemma 3.1.  $\square$

Let  $b \in (0, 1)$ . Define  $I(c)$  for  $c > 0$  as

$$I(c) = \sum_{n=0}^{\infty} \int_0^{2\pi} \exp\left(c \sum_{k=0}^n (\cos(b^{-k}u) - 1)\right) du.$$

Let  $D = \begin{pmatrix} \alpha & -\beta \\ \beta & \alpha \end{pmatrix}$  with  $\beta \neq 0$  and  $\alpha^2 + \beta^2 < 1$ . Let  $E$  be a square in  $\mathbf{R}^2$  having the area  $4\pi^2$  with a vertex at 0. Define  $J(c, y, E)$  for  $c > 0$  and  $y \in \mathbf{R}^2$  satisfying  $|y| = 1$  as

$$J(c, y, E) = \sum_{n=0}^{\infty} \int_E \exp\left(c \sum_{k=0}^n (\cos(\langle D'^{-k}z, y \rangle) - 1)\right) dz.$$

- Lemma 3.3.** (i)  $I(c) < \infty$  for all  $c > 0$ .  
 (ii)  $\sup_{|y|=1} J(c, y, E) < \infty$  for all  $c > 0$ .

*Proof.* We first prove the assertion (i). Let  $N \in \mathbf{Z}_+$  be sufficiently large and let  $\delta$  be an arbitrary real number. Define sequences  $\phi_l(\delta)$  for  $l \in \mathbf{Z}_+$  and  $a_m$  for  $m \in \mathbf{Z}_+$  as

$$\phi_l(\delta) = \sum_{n=0}^l \int_0^{2\pi} \exp\left(c \sum_{k=0}^n (\cos(b^{-kN}(v + \delta)) - 1)\right) dv,$$

and

$$a_m = \inf_{0 \leq x \leq 2\pi} (1 - \cos(b^N(x + 2m\pi) + \delta)).$$

Denote  $M = [b^{-N}] + 1$  and  $r = b^N(2M/3 + e^{-c}M/3)$ , where  $[x]$  stands for the largest integer not exceeding a real number  $x$ . We have

(3.2)

$$\begin{aligned} \phi_l(\delta) &= \phi_0(\delta) + b^N \sum_{n=1}^l \int_0^{b^{-N}2\pi} \exp\left(c \sum_{k=0}^n (\cos(b^{-(k-1)N}(u + b^{-N}\delta)) - 1)\right) du \\ &\leq \phi_0(\delta) + b^N \sum_{n=1}^l \sum_{m=0}^{M-1} \int_0^{2\pi} \exp\left(c \sum_{k=0}^n (\cos(b^{-(k-1)N}(v + 2m\pi + b^{-N}\delta)) - 1)\right) dv \\ &\leq \phi_0(\delta) + b^N \sum_{m=0}^{M-1} \phi_{l-1}(2m\pi + b^{-N}\delta) \exp(-ca_m). \end{aligned}$$

Since  $N$  is sufficiently large, so is  $M$  and we can assume that the number of  $m$  satisfying  $a_m \geq 1$  for  $0 \leq m \leq M - 1$  is more than  $M/3$ . Hence we see that  $0 < r < 1$  and

$$b^N \sum_{m=0}^{M-1} \exp(-ca_m) \leq r.$$

Noting that  $\phi_0(\delta) \leq 2\pi$ , we obtain from (3.2) that

$$\phi_l(\delta) \leq \sum_{j=0}^l 2\pi r^j \leq \frac{2\pi}{1-r}.$$

It follows that

$$\begin{aligned} (3.3) \quad I(c) &= \lim_{l \rightarrow \infty} \sum_{n=0}^{(l+1)N-1} \int_0^{2\pi} \exp\left(c \sum_{k=0}^n (\cos(b^{-k}u) - 1)\right) du \\ &\leq \lim_{l \rightarrow \infty} \sum_{n=0}^l \sum_{j=0}^{N-1} \int_0^{2\pi} \exp\left(c \sum_{k=0}^n (\cos(b^{-(kN+j)}u) - 1)\right) du \\ &= \lim_{l \rightarrow \infty} \sum_{n=0}^l \sum_{j=0}^{N-1} b^j \int_0^{2\pi b^{-j}} \exp\left(c \sum_{k=0}^n (\cos(b^{-kN}v) - 1)\right) dv \\ &\leq \lim_{l \rightarrow \infty} \sum_{n=0}^l \sum_{j=0}^{N-1} \sum_{m=0}^{[b^{-j}]} b^j \int_0^{2\pi} \exp\left(c \sum_{k=0}^n (\cos(b^{-kN}(u + 2m\pi)) - 1)\right) du \\ &= \lim_{l \rightarrow \infty} \sum_{j=0}^{N-1} \sum_{m=0}^{[b^{-j}]} b^j \phi_l(2m\pi) \leq \frac{4N\pi}{1-r} < \infty. \end{aligned}$$

Next we prove the assertion (ii). Let  $D = b \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix}$  with  $b = \sqrt{\alpha^2 + \beta^2}$  and  $0 \leq \theta < 2\pi$ . We continue to use  $M$  and  $N$  as above. Let  $\xi \in \mathbf{R}^2$  be arbitrary. Define



a sequence  $\Phi_l(\xi, y, E)$  for  $l \in \mathbf{Z}_+$  as

$$\Phi_l(\xi, y, E) = \sum_{n=0}^l \int_E \exp \left( c \sum_{k=0}^n (\cos \langle (D')^{-kN}(z + \xi), y \rangle - 1) \right) dz.$$

Denote  $E_1 = \begin{pmatrix} \cos N\theta & -\sin N\theta \\ \sin N\theta & \cos N\theta \end{pmatrix} E$  and denote the vertices of  $E_1$  by  $\{0, e_1, e_2, e_1 + e_2\}$ . Define  $a(m_1, m_2)$  for  $m_1, m_2 \in \mathbf{Z}_+$  as

$$a(m_1, m_2) = \inf_{x \in E_1} \left( 1 - \cos \left\langle (D')^N \left( x + \sum_{j=1}^2 m_j e_j \right) + \xi, y \right\rangle \right).$$

We have, as in (3.2),

$$\begin{aligned} & \Phi_l(\xi, y, E) - \Phi_0(\xi, y, E) \\ &= b^{2N} \sum_{n=1}^l \int_{b^{-N}E_1} \exp \left( c \sum_{k=0}^n (\cos \langle (D')^{-(k-1)N}(z + (D')^{-N}\xi), y \rangle - 1) \right) dz \\ &\leq b^{2N} \sum_{n=1}^l \sum_{m_1=0}^{M-1} \sum_{m_2=0}^{M-1} \int_{E_1} \exp \left( c \sum_{k=0}^n (\cos \langle (D')^{-(k-1)N}(z + \sum_{j=1}^2 m_j e_j + (D')^{-N}\xi), y \rangle - 1) \right) dz \\ &\leq b^{2N} \sum_{m_1=0}^{M-1} \sum_{m_2=0}^{M-1} \Phi_{l-1} \left( \sum_{j=1}^2 m_j e_j + (D')^{-N}\xi, y, E_1 \right) \exp(-ca(m_1, m_2)). \end{aligned}$$

Since  $M$  is sufficiently large, we can assume that there is a positive absolute constant  $\delta \in (0, 1)$  such that the number of  $(m_1, m_2)$  for  $0 \leq m_1, m_2 \leq M - 1$  satisfying  $a(m_1, m_2) \geq 1$  is more than  $\delta M^2$ . Denote  $s = b^{2N}((1 - \delta)M^2 + \delta M^2 e^{-c})$ . Then we see that  $0 < s < 1$  and

$$b^{2N} \sum_{m_1=0}^{M-1} \sum_{m_2=0}^{M-1} \exp(-ca(m_1, m_2)) \leq s.$$

Noting that

$$\Phi_0(\xi, y, E) \leq 4\pi^2,$$

we have

$$\Phi_l(\xi, y, E) \leq \sum_{j=0}^l 4\pi^2 s^j \leq \frac{4\pi^2}{1-s}.$$

Hence we obtain by the same manner in (3.3) that

$$\sup_{|y|=1} J(c, y, E) \leq \frac{8\pi^2 N}{1-s} \quad \text{for } \forall c > 0.$$

Thus the proof is complete. □

Proof of Theorem 3.1. We can assume without loss of generality that there is no proper subspace  $W$  such that  $P(X(n) \in W \text{ for } n \in \mathbf{Z}) = 1$ . Let  $S = RAR^{-1}$  be the real Jordan canonical form of the matrix  $A$  with a real invertible  $d \times d$  matrix  $R$ . Since we have

$$\{RX(n+1), n \in \mathbf{Z}\} \stackrel{d}{=} \{SRX(n), n \in \mathbf{Z}\},$$

the random sequence  $\{RX(n), n \in \mathbf{Z}\}$  is shift  $S$ -selfsimilar and additive. If  $\{RX(n), n \in \mathbf{Z}\}$  is transient, then  $\{X(n), n \in \mathbf{Z}\}$  is also transient. Thus we can assume that  $A = S$ . There are two possible cases.

CASE 1. An eigenvalue of  $S$  is real.

CASE 2. No eigenvalue of  $S$  is real.

Let  $H_l = \{(x_1, \dots, x_d)' \in \mathbf{R}^d : x_j = 0 \text{ for } 1 \leq j \leq d - l\}$  and let  $P_l$  be the orthogonal projector to  $H_l$  for  $l = 1, 2$ . Define the random sequence  $\{Y_l(n), n \in \mathbf{Z}\}$  by  $Y_l(n) = P_l X(n)$  for  $l = 1, 2$ . In Case 1, there is a Jordan block with a real eigenvalue  $b^{-1} \in (-\infty, -1) \cup (1, \infty)$  in  $S$ . We can assume that this Jordan block lies in the lowest position in  $S$ . Thus  $\{Y_1(n), n \in \mathbf{Z}\}$  is a non-zero shift  $b^{-1}$ -selfsimilar additive random sequence on  $H_1$ . In Case 2,  $\{Y_2(n), n \in \mathbf{Z}\}$  is a non-zero shift  $P_2 S$ -selfsimilar additive random sequence on  $H_2$ . Thus it is enough to prove the transience in the case of  $d = 1$  and in the case where  $d = 2$  and  $A^{-1} = D$  with  $\beta \neq 0$  and  $\alpha^2 + \beta^2 < 1$ . We treat only the latter case. The proof of the first case is similar by virtue of (i) of Lemma 3.3 and is omitted. By using the inequalities  $|x| \leq e^{|x| - 1}$  and  $|\cos x| - 1 \leq 4^{-1}(\cos 2x - 1)$ , we obtain from (2.5) that

$$\begin{aligned} (3.4) \quad |\widehat{\mu}_n(z)|^2 &= \prod_{k=0}^{\infty} \left| \int_{\mathbf{R}^2} \cos \langle (D')^{k-n} z, x \rangle \rho_1 * \bar{\rho}_1(dx) \right| \\ &\leq \exp \left( \sum_{k=0}^{\infty} \int_{\mathbf{R}^2} (|\cos \langle (D')^{k-n} z, x \rangle| - 1) \rho_1 * \bar{\rho}_1(dx) \right) \\ &\leq \exp \left( 4^{-1} \sum_{k=0}^{\infty} \int_{\mathbf{R}^2} (\cos \langle 2(D')^{k-n} z, x \rangle - 1) \rho_1 * \bar{\rho}_1(dx) \right). \end{aligned}$$

If  $\rho_1 * \bar{\rho}_1(dx) = \delta_0(dx)$ , then  $\rho_1(dx) = \delta_a(dx)$  for some  $a \in \mathbf{R}^d$  and hence  $\{X(n), n \in \mathbf{Z}\}$  has deterministic increments and transient. Note that  $a \neq 0$  because  $\{X(n), n \in \mathbf{Z}\}$  is not a zero sequence. Thus we can choose a compact set  $K$  in  $\mathbf{R}^2$  not containing 0 and a positive number  $a_0$  such that  $C := \rho_1 * \bar{\rho}_1(K) > 0$  and  $a_0 \sup_{y \in K} |y| \leq \pi$ . Let  $E_1 = [0, 2\pi] \times [0, 2\pi]$ ,  $E_2 = [-2\pi, 0] \times [0, 2\pi]$ ,  $E_3 = [-2\pi, 0] \times [-2\pi, 0]$  and  $E_4 = [0, 2\pi] \times [-2\pi, 0]$ . Then by using Jensen's inequality

ity and letting  $w = 2|x|z$ , we conclude from (3.4) and (ii) of Lemma 3.3 that

$$\begin{aligned} & \sum_{n=0}^{\infty} \int_{|z| \leq a_0} |\widehat{\mu}_n(z)| dz \\ & \leq \sum_{n=0}^{\infty} \int_{|z| \leq a_0} \exp \left( 8^{-1} \sum_{k=0}^{\infty} \int_K (\cos \langle 2(D')^{k-n}z, x \rangle - 1) \rho_1 * \bar{\rho}_1(dx) \right) dz \\ & \leq \sum_{n=0}^{\infty} \int_K \frac{\rho_1 * \bar{\rho}_1(dx)}{4C|x|^2} \sum_{j=1}^4 \int_{E_j} \exp \left( 8^{-1}C \sum_{k=0}^{\infty} \left( \cos \left\langle (D')^{k-n}w, \frac{x}{|x|} \right\rangle - 1 \right) \right) dw \\ & \leq \sum_{j=1}^4 \int_K J \left( \frac{C}{8}, \frac{x}{|x|}, E_j \right) \frac{\rho_1 * \bar{\rho}_1(dx)}{4C|x|^2} < \infty. \end{aligned}$$

It follows from Lemma 3.2 that  $\{X(n), n \in \mathbf{Z}\}$  is transient. □

#### 4. Rate of growth I

In this section, let  $\{X(n), n \in \mathbf{Z}\}$  be an increasing shift  $a$ -self-similar additive random sequence with non-deterministic increments, that is,  $a > 1$ ,  $S_{\rho_1} \subset [0, \infty)$  and  $\rho_1(dx) \neq \delta_c(dx)$  for any  $c \geq 0$ . Note that all distributions  $\mu_n$  are continuous thanks to Wolfe’s theorem in [35]. We investigate the rate of growth of  $\{X(n), n \in \mathbf{Z}\}$  in the “liminf” case. We state the results only as  $n \rightarrow \infty$  except in Theorem 4.1. The results and their proofs as  $n \rightarrow -\infty$  are similar and omitted. Define

$$\mathcal{G}_0 = \{g(x) : g(x) \text{ is positive and decreasing on } [0, \infty)\}.$$

The abbreviation “i.o.” means “infinitely often”. First we study some preliminary results.

**Lemma 4.1.** *Let  $B$  be a real invertible  $d \times d$  matrix all of whose eigenvalues have absolute values less than 1. Let  $\zeta_n, n \geq 1$ , be  $B$ -decomposable distributions on  $\mathbf{R}^d$  such that*

$$(4.1) \quad \widehat{\zeta}_n(z) = \widehat{\zeta}_n(B'z)\widehat{\eta}_n(z),$$

where  $\eta_n$  are probability distributions on  $\mathbf{R}^d$  satisfying  $\int_{\mathbf{R}^d} \log(1 + |x|)\eta_n(dx) < \infty$ . Suppose that  $\eta_n$  converges weakly to a probability distribution  $\eta_\infty$  on  $\mathbf{R}^d$  as  $n \rightarrow \infty$  and

$$(4.2) \quad \limsup_{N \rightarrow \infty} \sup_{n \geq 1} \int_{|x| \geq N} \log(1 + |x|)\eta_n(dx) = 0.$$

Then  $\zeta_n$  converges weakly to some  $B$ -decomposable distribution  $\zeta_\infty$  on  $\mathbf{R}^d$  as  $n \rightarrow \infty$ ,

which is defined by

$$\widehat{\zeta}_\infty(z) = \widehat{\zeta}_\infty(B^l z) \widehat{\eta}_\infty(z).$$

Proof. Fix  $z \in \mathbf{R}^d$  and let  $M \in \mathbf{N}$ . We obtain from (4.1) that

$$(4.3) \quad \widehat{\zeta}_n(z) = \prod_{l=0}^{M-1} \widehat{\eta}_n((B^l)^l z) \prod_{l=M}^{\infty} \left( 1 + \int_{\mathbf{R}^d} (e^{i\langle z, B^l x \rangle} - 1) \eta_n(dx) \right).$$

Choose  $k \in \mathbf{N}$  satisfying  $\|B^k\| < 1$ . Then we have

$$(4.4) \quad \begin{aligned} & \sum_{l=M}^{\infty} \left| \int_{|x| \leq \|B^k\|^{-l/(2k)}} (e^{i\langle z, B^l x \rangle} - 1) \eta_n(dx) \right| \\ & \leq \sum_{l=M}^{\infty} \int_{|x| \leq \|B^k\|^{-l/(2k)}} |\langle z, B^l x \rangle| \eta_n(dx) \\ & \leq c_1 \sum_{l=M}^{\infty} |z| \|B^k\|^{l/(2k)} \leq c_2 |z| \|B^k\|^{M/(2k)} \end{aligned}$$

and

$$(4.5) \quad \begin{aligned} & \sum_{l=M}^{\infty} \left| \int_{|x| \geq \|B^k\|^{-l/(2k)}} (e^{i\langle z, B^l x \rangle} - 1) \eta_n(dx) \right| \\ & \leq 2 \sum_{l=M}^{\infty} \int_{|x| \geq \|B^k\|^{-l/(2k)}} \eta_n(dx) \\ & \leq c_3 \int_{|x| \geq \|B^k\|^{-M/(2k)}} \log(2 + |x|) \eta_n(dx), \end{aligned}$$

where  $c_j$ ,  $j = 1, 2, 3$ , are positive constants. We see from (4.2), (4.4) and (4.5) that

$$(4.6) \quad \begin{aligned} & \limsup_{M \rightarrow \infty} \sup_{n \geq 1} \sum_{l=M}^{\infty} \left| \int_{\mathbf{R}^d} (e^{i\langle z, B^l x \rangle} - 1) \eta_n(dx) \right| \\ & \leq \limsup_{M \rightarrow \infty} \left( c_2 |z| \|B^k\|^{M/(2k)} + c_3 \sup_{n \geq 1} \int_{|x| \geq \|B^k\|^{-M/(2k)}} \log(2 + |x|) \eta_n(dx) \right) = 0. \end{aligned}$$

Note that

$$\lim_{n \rightarrow \infty} \prod_{l=0}^{M-1} \widehat{\eta}_n((B^l)^l z) = \prod_{l=0}^{M-1} \widehat{\eta}_\infty((B^l)^l z).$$

It follows from (4.3) and (4.6) that

$$\lim_{n \rightarrow \infty} \widehat{\zeta}_n(z) = \lim_{n \rightarrow \infty} \prod_{l=0}^{\infty} \widehat{\eta}_n((B')^l z) = \prod_{l=0}^{\infty} \widehat{\eta}_{\infty}((B')^l z) = \widehat{\zeta}_{\infty}(z).$$

Thus  $\widehat{\zeta}_n$  converges weakly to  $\widehat{\zeta}_{\infty}$  as  $n \rightarrow \infty$ . □

For two positive functions  $f(t)$  and  $g(t)$  on  $[1, \infty)$ , we define a relation  $f(t) \asymp g(t)$  as  $\limsup_{t \rightarrow \infty} g(t)/f(t) < \infty$  and  $\liminf_{t \rightarrow \infty} g(t)/f(t) > 0$ , and a relation  $f(t) \sim g(t)$  as  $\lim_{t \rightarrow \infty} g(t)/f(t) = 1$ . As mentioned in Section 1, a positive measurable function  $f(t)$  on  $(0, \infty)$  is said to belong to the class  $OR$  if, for every  $\delta > 1$ ,  $\limsup_{t \rightarrow \infty} f(\delta t)/f(t) < \infty$  and  $\liminf_{t \rightarrow \infty} f(\delta t)/f(t) > 0$ . The Laplace transform of a probability distribution  $\mu$  on  $[0, \infty)$  is denoted by  $L_{\mu}(t)$  for  $t \geq 0$ , that is,  $L_{\mu}(t) = \int_{[0, \infty)} e^{-tx} \mu(dx)$ . The following lemma is a version of Theorem 1 of [8]. The proof is similar and omitted.

**Lemma 4.2.** *Let  $\mu$  be a probability distribution on  $[0, \infty)$ . Then the following are equivalent.*

- (i)  $\mu([0, 1/t]) \in OR$ .
- (ii)  $L_{\mu}(t) \in OR$ .
- (iii)  $\mu([0, 1/t]) \asymp L_{\mu}(t)$  as  $t \rightarrow \infty$ .

Define a regularly varying function  $K_{\lambda}(x)$  on  $(0, \infty)$  with the index  $-\log \lambda / \log b$  for a probability distribution  $\rho$  on  $[0, \infty)$  with  $\lambda := \rho(\{0\}) > 0$  as

$$(4.7) \quad K_{\lambda}(x) = x^{-\log \lambda / \log b} \exp \left( \int_1^x \frac{\log \lambda - \log L_{\rho}(u)}{u \log b} du \right).$$

The following proposition is an extension of Theorem 1.6 of [28] concerning one-sided selfdecomposable distributions.

**Proposition 4.1.** *Let  $B = b \in (0, 1)$  and let  $\mu$  be a  $B$ -decomposable distribution on  $[0, \infty)$  with  $\rho$  in (2.1). If  $\lambda := \rho(\{0\}) > 0$ , then*

$$(4.8) \quad \mu \left( \left[ 0, \frac{1}{t} \right] \right) \asymp K_{\lambda}(t) \quad \text{as } t \rightarrow \infty.$$

Proof. We have by (2.1)

$$L_{\mu}(t) = \prod_{n=0}^{\infty} L_{\rho}(b^n t).$$

Hence we get that

$$\lim_{t \rightarrow \infty} \frac{L_\mu(b^{-1}t)}{L_\mu(t)} = \lim_{t \rightarrow \infty} L_\rho(b^{-1}t) = \lambda.$$

Since  $L_\mu(t)$  is decreasing, it follows that  $L_\mu(t) \in OR$ . Define  $N(t) = \lceil -\log t / \log b \rceil$ . Since  $tb^{N(t)} \asymp 1$  and

$$L_\mu(t) = \prod_{n=0}^{N(t)} L_\rho(b^n t) \prod_{n=0}^{\infty} L_\rho(b^{N(t)+n+1}t),$$

we see that

$$\begin{aligned} L_\mu(t) &\asymp \prod_{n=0}^{N(t)} L_\rho(b^n t) = \exp\left(\sum_{n=0}^{N(t)} \log L_\rho(b^n t)\right) \\ &\asymp \exp\left(-\int_1^t \frac{\log L_\rho(u)}{u \log b} du\right) = K_\lambda(t). \end{aligned}$$

Therefore, we obtain (4.8) from Lemma 4.2. □

**Proposition 4.2.** *Let  $B = b \in (0, 1)$  and let  $\mu$  be a  $B$ -decomposable distribution on  $[0, \infty)$  with  $\rho$  in (2.1). Then there are positive constants  $c_1$  and  $c_2$  such that, for  $0 < t < b$  and  $0 < \varepsilon < 1 - b$ ,*

$$(4.9) \quad \mu([0, t]) \leq c_1 \exp\left(-\int_t^1 \frac{\log \rho([0, u])}{u \log b} du\right)$$

and

$$(4.10) \quad \mu([0, t]) \geq c_2 \exp\left(\int_{b\varepsilon t}^1 \frac{\log \rho([0, u])}{u \log(b^{-1}(1 - \varepsilon))} du\right).$$

Proof. We use  $c_j, j \geq 1$ , as positive constants. We see from (2.1) that

$$(4.11) \quad \mu([0, t]) = \int_{[0,t]} \mu([0, b^{-1}(t-x)])\rho(dx).$$

Define  $\tilde{N}(t) = \lceil \log t / \log b \rceil$  and  $M(t) = \lceil -\log t / \log(b^{-1}(1 - \varepsilon)) \rceil$ . We have by (4.11)

$$(4.12) \quad \begin{aligned} \mu([0, t]) &\leq \mu([0, b^{-1}t])\rho([0, t]) \\ &\leq \prod_{n=0}^{\tilde{N}(t)} \rho([0, b^{-n}t])\mu([0, b^{-\tilde{N}(t)-1}t]) \end{aligned}$$

$$\begin{aligned} &\leq c_3 \exp \left( \sum_{n=0}^{\tilde{N}(t)} \log \rho([0, b^{-n}t]) \right) \\ &\leq c_1 \exp \left( - \int_t^1 \frac{\log \rho([0, u])}{u \log b} du \right). \end{aligned}$$

On the other hand, we see from (4.11) that, for any  $\varepsilon \in (0, 1 - b)$ ,

$$\begin{aligned} \mu([0, t]) &\geq \mu([0, (b^{-1}(1 - \varepsilon))t])\rho([0, \varepsilon t]) \\ &\geq \prod_{n=0}^{M(t)} \rho([0, \varepsilon(b^{-1}(1 - \varepsilon))^n t])\mu([0, (b^{-1}(1 - \varepsilon))^{M(t)+1}t]) \\ &\geq c_4 \exp \left( \sum_{n=0}^{M(t)} \log \rho([0, \varepsilon(b^{-1}(1 - \varepsilon))^n t]) \right) \\ &\geq c_2 \exp \left( \int_{b\varepsilon t}^1 \frac{\log \rho([0, u])}{u \log(b^{-1}(1 - \varepsilon))} du \right). \end{aligned}$$

Thus the proof of the proposition is complete. □

REMARK 4.1. Under the same assumption as in Proposition 4.2, we see from (4.9) that, if  $\rho(\{0\}) \neq 1$ , then

$$\int_0^1 \mu([0, t])t^{-1} dt < \infty.$$

Now we present a key theorem in this section.

**Theorem 4.1.** *Let  $g(x) \in \mathcal{G}_0$ . If*

$$(4.13) \quad \int_0^\infty P(X(0) \leq g(x)) dx < \infty \quad (\text{resp. } = \infty),$$

then

$$(4.14) \quad P(X(n) \leq a^n g(n) \text{ i.o. as } n \rightarrow \infty) = 0 \quad (\text{resp. } = 1)$$

and

$$(4.15) \quad P(X(n) \leq a^n g(-n) \text{ i.o. as } n \rightarrow -\infty) = 0 \quad (\text{resp. } = 1).$$

Proof. Suppose that

$$\int_0^\infty P(X(0) \leq g(x)) dx < \infty,$$

that is,

$$\sum_{n=0}^{\infty} P(X(0) \leq g(n)) < \infty.$$

Then we have by the shift  $a$ -selfsimilarity

$$\sum_{n=0}^{\infty} P(X(n) \leq a^n g(n)) < \infty.$$

Hence we see from the Borel-Cantelli lemma that almost surely  $X(n) > a^n g(n)$  for all large  $n$ , that is,

$$P(X(n) \leq a^n g(n) \quad \text{i.o. as } n \rightarrow \infty) = 0.$$

Conversely, suppose that

$$\int_0^{\infty} P(X(0) \leq g(x)) dx = \infty,$$

that is,

$$\sum_{n=0}^{\infty} P(X(0) \leq g(n)) = \infty.$$

Then we get by the shift  $a$ -selfsimilarity

$$(4.16) \quad \sum_{n=0}^{\infty} P(X(n) \leq a^n g(n)) = \infty.$$

Define the events  $A_n$  and a sequence  $s_n$  with  $l \in \mathbf{N}$  as

$$A_n = \{\omega : X(n) \leq a^n g(n)\}$$

and

$$s_n = P(X(jl) - X(nl) > a^{jl} g(jl) \quad \text{for } \forall j \geq n+1).$$

We find from (4.16) that there is  $j$  with  $0 \leq j \leq l-1$  such that  $\sum_{n=0}^{\infty} P(A_{nl+j}) = \infty$ . We assume that  $j = 0$ . Discussion in the case  $j \neq 0$  is similar. We have by the independence of increments

$$1 \geq P\left(\bigcup_{n=0}^{\infty} A_{nl}\right) \geq \sum_{n=0}^{\infty} P\left(\left(\bigcup_{j=n+1}^{\infty} A_{jl}\right)^c \cap A_{nl}\right) \geq \sum_{n=0}^{\infty} P(A_{nl})s_n.$$



Hence we see that there is a subsequence  $S(k) := s_{n_k}$  such that  $S(k) \rightarrow 0$  as  $k \rightarrow \infty$ . Define a sequence  $T(k)$  and a sequence  $p_k(x)$  of functions on  $[0, \infty)$  as

$$T(k) = P(X(nl) > a^{nl}g(nl) \quad \text{for } \forall n \geq n_k + 1)$$

and

$$p_k(x) = P(X(nl) - X((n_k + 1)l) > a^{nl}g(nl) - a^{(n_k+1)l}x \quad \text{for } \forall n \geq n_k + 2).$$

Note that  $p_k(x)$  is increasing and bounded in  $x$ . We have

$$S(k) = \int_{(g((n_k+1)l), \infty)} p_k(x)\rho_l(dx)$$

and

$$T(k) = \int_{(g((n_k+1)l), \infty)} p_k(x)\mu_0(dx).$$

We show that  $T(k) \rightarrow 0$  as  $k \rightarrow \infty$  by considering two possible cases. Case (i).  $M := \sup S_{\mu_0} < \infty$ ; Case (ii).  $M = \infty$ . In Case (i) we can choose, for any  $\varepsilon > 0$ , sufficiently large  $l$  such that  $M - \varepsilon < \sup S_{\rho_l}$ . If  $\lim_{x \rightarrow \infty} g(x) \geq M$ , then trivially  $T(k) = 0$  for all  $k \geq 0$ . Thus we can and do assume that  $\lim_{x \rightarrow \infty} g(x) < M$ . Hence we obtain that, for sufficiently small  $\varepsilon > 0$ ,

$$0 = \lim_{k \rightarrow \infty} S(k) \geq \lim_{k \rightarrow \infty} p_k(M - \varepsilon)\rho_l([M - \varepsilon, M]),$$

that is,  $\lim_{k \rightarrow \infty} p_k(M - \varepsilon) = 0$ . We have

$$T(k) \leq \int_{[0, M - \varepsilon)} p_k(M - \varepsilon)\mu_0(dx) + \mu_0([M - \varepsilon, M]).$$

Letting  $k \rightarrow \infty$  and then  $\varepsilon \downarrow 0$ , we see from the continuity of  $\mu_0$  that  $\lim_{k \rightarrow \infty} T(k) = 0$ . In Case (ii), we can prove by the same way that  $\lim_{k \rightarrow \infty} T(k) = 0$ . Denote the events  $B_k$  as

$$B_k = \{\omega : X(n) \leq a^n g(n) \text{ for some } n \geq n_k l\}.$$

Then  $B_k$  is decreasing and  $P(B_k) \geq 1 - T(k)$ . It follows that

$$P(B_k) = P\left(\bigcap_{k=1}^{\infty} B_k\right) = 1,$$

that is,

$$P(X(n) \leq a^n g(n) \quad \text{i.o. as } n \rightarrow \infty) = 1.$$

The proof of (4.15) is similar and omitted. Thus we have proved the theorem. □

**Corollary 4.1.** *Let  $g(x) \in \mathcal{G}_0$  and  $c \in [0, \infty]$ . Then*

$$(4.17) \quad \liminf_{n \rightarrow \infty} \frac{X(n)}{a^n g(n)} = c \quad \text{a.s.}$$

*if and only if*

$$(4.18) \quad \int_0^\infty P(X(0) \leq \delta g(x)) dx \begin{cases} < \infty & \text{for } 0 < \delta < c \\ = \infty & \text{for } \delta > c. \end{cases}$$

*Thus, for any  $g(x) \in \mathcal{G}_0$ , there exists  $c \in [0, \infty]$  such that (4.17) holds.*

**Proof.** The corollary is clear from Theorem 4.1. □

**REMARK 4.2.** We see from Remark 4.1 and Corollary 4.1 that, for any  $\varepsilon \in (0, a)$ ,

$$\lim_{n \rightarrow \infty} \frac{X(n)}{(a - \varepsilon)^n} = \infty \quad \text{a.s.}$$

**Theorem 4.2.** *There exists  $g(x) \in \mathcal{G}_0$  satisfying*

$$(4.19) \quad \liminf_{n \rightarrow \infty} \frac{X(n)}{a^n g(n)} = 1 \quad \text{a.s.}$$

*if and only if  $\rho_1(\{0\}) = 0$ .*

**Proof.** Suppose that  $\rho_1(\{0\}) > 0$ . Since  $\mu_0$  is  $a^{-1}$ -decomposable, we have as in (4.11)

$$(4.20) \quad \begin{aligned} \mu_0([0, x]) &= \int_{[0, x]} \mu_0([0, a(x - u)]) \rho_1(du) \\ &\geq \mu_0([0, ax]) \rho_1(\{0\}). \end{aligned}$$

If there is  $g(x) \in \mathcal{G}_0$  satisfying (4.19), then we get by Corollary 4.1 that

$$\int_0^\infty \mu_0([0, \sqrt{a} g(x)]) dx = \infty \quad \text{and} \quad \int_0^\infty \mu_0 \left( \left[ 0, \frac{g(x)}{\sqrt{a}} \right] \right) dx < \infty.$$

But they contradict (4.20). Hence if  $\rho_1(\{0\}) > 0$ , then there is no  $g(x) \in \mathcal{G}_0$  satisfying (4.19). Conversely, suppose that  $\rho_1(\{0\}) = 0$ . If  $M := \inf S_{\rho_1} > 0$ , then  $\inf S_{\mu_0} = M(1 - a^{-1})^{-1} > 0$ . Define  $g(x) = M(1 - a^{-1})^{-1}$  on  $[0, \infty)$ . Then we have (4.18) with  $c = 1$  and hence (4.19) by Corollary 4.1. Thus it is enough to construct  $g(x) \in \mathcal{G}_0$  satisfying (4.19) under the assumption that  $0 \in S_{\rho_1}$  and  $\rho_1(\{0\}) = 0$ .

We see from the assumption that there is a positive and decreasing sequence  $a_n$  such that

$$(4.21) \quad \sum_{n=0}^{\infty} \rho_1([0, a_n]) < \infty.$$

We see as in (4.12) that

$$(4.22) \quad \mu_0([0, x]) \leq \mu_0([0, ax])\rho_1([0, x]).$$

Hence we obtain that

$$(4.23) \quad \mu_0([0, a^{-1}a_n]) \leq \mu_0([0, a_n])\rho_1([0, a_n])$$

and

$$(4.24) \quad \mu_0([0, aa_n]) \geq \frac{\mu_0([0, a_n])}{\rho_1([0, a_n])}.$$

We define an increasing sequence  $b_n$  by induction as follows. Set  $b_0 = 0$ . Assume that  $b_n$  are defined for  $0 \leq n \leq k$ . Then we define  $b_{k+1}$  considering two cases. If  $\mu_0([0, a_k]) \leq \rho_1([0, a_k])$ , then choose  $b_{k+1}$  satisfying

$$\rho_1([0, a_k]) \leq \mu_0([0, a_k])(b_{k+1} - b_k) \leq 1.$$

If  $\mu_0([0, a_k]) > \rho_1([0, a_k])$ , then set  $b_{k+1} = b_k + 1$ . Note that  $b_{n+1} \geq b_n + 1$  and hence  $\lim_{n \rightarrow \infty} b_n = \infty$ . Define  $g(x) \in \mathcal{G}_0$  as  $g(x) = a_n$  on  $[b_n, b_{n+1})$  for  $n \in \mathbf{Z}_+$ . Then we have by (4.21) and (4.23)

$$\begin{aligned} \int_0^{\infty} \mu_0([0, a^{-1}g(x)]) dx &\leq \sum_{n=0}^{\infty} \mu_0([0, a_n])\rho_1([0, a_n])(b_{n+1} - b_n) \\ &\leq \sum_{n=0}^{\infty} \rho_1([0, a_n]) < \infty. \end{aligned}$$

On the other hand we get by (4.24)

$$\int_0^{\infty} \mu_0([0, ag(x)]) dx \geq \sum_{n=1}^{\infty} \frac{\mu_0([0, a_n])}{\rho_1([0, a_n])}(b_{n+1} - b_n) = \infty.$$

It follows from Corollary 4.1 that there is  $c \in [a^{-1}, a]$  satisfying (4.18). Thus we get (4.19) using  $cg(n)$  in place of  $g(n)$ .  $\square$

**Corollary 4.2.** *Let  $g(x) \in \mathcal{G}_0$ . Let  $K_\lambda(x)$  be the function defined in (4.7) with  $\rho = \rho_1$  and  $b = a^{-1}$ . Suppose that  $\lambda := \rho_1(\{0\}) > 0$ . If*

$$\int_0^\infty K_\lambda \left( \frac{1}{g(x)} \right) dx = \infty \quad (\text{resp. } < \infty),$$

then

$$\liminf_{n \rightarrow \infty} \frac{X(n)}{a^n g(n)} = 0 \quad (\text{resp. } = \infty) \quad \text{a.s.}$$

Proof. We see from Proposition 4.1 that

$$\int_0^\infty P(X(0) \leq \delta g(x)) dx = \infty \quad (\text{resp. } < \infty) \quad \text{for } \forall \delta > 0$$

if and only if

$$\int_0^\infty K_\lambda \left( \frac{1}{g(x)} \right) dx = \infty \quad (\text{resp. } < \infty).$$

Therefore the corollary follows from Corollary 4.1.  $\square$

In the following theorem, we fix  $a > 1$  and consider the family of all increasing shift  $a$ -selfsimilar additive random sequences  $\{X(n), n \in \mathbf{Z}\}$ .

**Theorem 4.3.** *Let  $g(x) \in \mathcal{G}_0$ . There exists  $\{X(n), n \in \mathbf{Z}\}$  satisfying (4.19) if and only if*

$$(4.25) \quad \liminf_{x \rightarrow \infty} \frac{-\log g(x)}{\log x} = 0.$$

Proof. We use  $c_j$  as positive constants. Without loss of generality, we can assume that  $g(1) < 1$ . Suppose that (4.25) is not true and that there is  $\{X(n), n \in \mathbf{Z}\}$  satisfying (4.19). Then we see that  $\rho_1(\{0\}) = 0$  by Theorem 4.2 and there is  $L > 0$  such that

$$g(x) \leq x^{-L} \quad \text{on } [1, \infty).$$

Noting that  $\rho_1([0, u]) \downarrow 0$  as  $u \downarrow 0$ , we have by (4.9), for any  $\delta > 0$ ,

$$\begin{aligned} \int_0^\infty P(X(0) \leq \delta g(x)) dx &\leq 1 + \int_1^\infty P(X(0) \leq \delta x^{-L}) dx \\ &\leq 1 + c_1 \int_1^\infty \exp \left( \int_{\delta x^{-L}}^1 \frac{\log \rho_1([0, u])}{u \log a} du \right) dx < \infty. \end{aligned}$$

It follows from Corollary 4.1 that

$$\liminf_{n \rightarrow \infty} \frac{X(n)}{a^n g(n)} = \infty \quad \text{a.s.}$$

This is a contradiction. Thus if there is  $\{X(n), n \in \mathbf{Z}\}$  satisfying (4.19), then (4.25) is true. Conversely, suppose that the condition (4.25) is true. In case  $N := \lim_{x \rightarrow \infty} g(x) > 0$ , define  $\rho_1$  as  $\rho_1(\{(1 - a^{-1})N\}) = \rho_1(\{2(1 - a^{-1})N\}) = 2^{-1}$ . Then (4.19) is true by Corollary 4.1. Thus we can assume that  $N = 0$ . We show the existence of  $\{X(n), n \in \mathbf{Z}\}$  satisfying (4.19) by constructing the measure  $\rho_1$ . The condition (4.25) says that there are sequences  $x_n \uparrow \infty$  and  $\delta_n \downarrow 0$  for  $n \in \mathbf{Z}_+$  such that  $x_0 = 1, x_{n+1} > 2x_n$ ,

$$(4.26) \quad \varepsilon^{-1} a g(2^{-1} x_{n+1}) \leq e^{-1} g(x_n) \quad \text{with } \varepsilon = 1 - a^{-1/2}$$

and

$$(4.27) \quad g(x_n) \geq x_n^{-\delta_n}.$$

We construct  $\rho_1([0, u])$  together with  $n_k \uparrow \infty$  and  $M_k \uparrow \infty$  for  $k \in \mathbf{Z}_+$  by induction in such a way that with  $b_k := x_{n_k}$

$$M_{k+1} \geq M_k + 1 \text{ and } \rho_1([0, u]) = e^{-M_k \log a} \text{ on } [g(b_k), g(b_{k-1})) \text{ for } k \in \mathbf{Z}_+$$

and

$$(4.28) \quad 2^{-1} \leq \int_{2^{-1} b_k}^{b_k} \mu_0([0, \varepsilon^{-1} a g(x)]) dx + \int_{b_{k-1}}^{2^{-1} b_k} \mu_0([0, e^{-1} g(x)]) dx \leq 2 \text{ for } k \geq 1.$$

First set  $n_{-1} = n_0 = 0$  and  $M_0 = 0$ . Let  $l \geq 0$ . Let  $\{X^{(l)}(n), n \in \mathbf{Z}\}$  be an increasing shift  $a$ -self-similar additive random sequence with

$$\rho_1^{(l)}([0, u]) = \begin{cases} e^{-M_k \log a}, & \text{on } [g(b_k), g(b_{k-1})) \text{ for } 0 \leq k \leq l \\ 0, & \text{on } [0, g(b_l)]. \end{cases}$$

Denote the distribution of  $X^{(l)}(0)$  by  $\mu_0^{(l)}$ . Define, for  $1 \leq k \leq l$ ,

$$J^{(l)}(k) = \int_{2^{-1} b_k}^{b_k} \mu_0^{(l)}([0, \varepsilon^{-1} a g(x)]) dx + \int_{b_{k-1}}^{2^{-1} b_k} \mu_0^{(l)}([0, e^{-1} g(x)]) dx.$$

Assume that  $M_k \geq M_{k-1} + 1$  and  $2^{-1} + 2^{-l} \leq J^{(l)}(k) \leq 2 - 2^{-l}$  for  $1 \leq k \leq l$ . Temporarily set, for some  $n \geq n_l + 1$  and  $M \geq M_l + 1$ ,

$$\rho_1([0, u]) = \begin{cases} e^{-M_k \log a}, & \text{on } [g(b_k), g(b_{k-1})) \text{ for } 0 \leq k \leq l \\ e^{-M \log a}, & \text{on } [g(x_n), g(b_l)] \\ 0, & \text{on } [0, g(x_n)] \end{cases}$$

and define

$$I(n, M) = \int_{2^{-1}x_n}^{x_n} \mu_0([0, \varepsilon^{-1}ag(x)]) dx + \int_{b_l}^{2^{-1}x_n} \mu_0([0, e^{-1}g(x)]) dx.$$

Fix  $M \geq M_l + 1$ , then we obtain from (4.10) and (4.27) that

$$\begin{aligned} \liminf_{n \rightarrow \infty} I(n, M) &\geq \liminf_{n \rightarrow \infty} \int_{2^{-1}x_n}^{x_n} \mu_0([0, \varepsilon^{-1}ag(x)]) dx \\ &\geq \liminf_{n \rightarrow \infty} \mu_0([0, \varepsilon^{-1}ag(x_n)])2^{-1}x_n \\ &\geq c_2 \liminf_{n \rightarrow \infty} \exp\left(-\int_{g(x_n)}^1 \frac{M \log a}{u \log(a(1-\varepsilon))} du\right) x_n \\ &= c_2 \liminf_{n \rightarrow \infty} g(x_n)^{2M} x_n \geq c_2 \lim_{n \rightarrow \infty} x_n^{(1-2M\delta_n)} = \infty. \end{aligned}$$

On the other hand, fix  $n \geq n_l + 1$ , then we get by (4.9) and (4.26) that

$$\begin{aligned} \limsup_{M \rightarrow \infty} I(n, M) &\leq 2^{-1} \limsup_{M \rightarrow \infty} \mu_0([0, e^{-1}g(b_l)])x_n + \limsup_{M \rightarrow \infty} \int_{b_l}^{2^{-1}x_n} \mu_0([0, e^{-1}g(b_l)]) dx \\ &\leq \limsup_{M \rightarrow \infty} \mu_0([0, e^{-1}g(b_l)])x_n \\ &\leq c_3 \limsup_{M \rightarrow \infty} \exp\left(-\int_{e^{-1}g(b_l)}^{g(b_l)} \frac{M}{u} du\right) x_n \\ &= c_3 \lim_{M \rightarrow \infty} \exp(-M)x_n = 0. \end{aligned}$$

Hence we have  $I(n, M_l + 1) \geq 1$  for sufficiently large  $n$  satisfying  $n \geq n_l + 1$ . Since  $I(n, M)$  is continuous in  $M$  on account of Lemma 4.1, we can take  $M = M(n) \geq M_l + 1$  such that  $I(n, M(n)) = 1$  for sufficiently large  $n$ . Since  $M(n) \rightarrow \infty$  as  $n \rightarrow \infty$ ,  $\rho_1$  and  $\mu_0$  are convergent weakly to  $\rho_1^{(l)}$  and  $\mu_0^{(l)}$ , respectively as  $n \rightarrow \infty$  by virtue of Lemma 4.1. Hence we can choose sufficiently large  $n = n_{l+1}$  and define  $\rho_1^{(l+1)}$  such that  $M_{l+1} = M(n_{l+1})$  and  $2^{-1} + 2^{-l-1} \leq J^{(l+1)}(k) \leq 2 - 2^{-l-1}$  for  $1 \leq k \leq l + 1$ . Finally we define  $\rho_1$  as the weak limit of  $\rho_1^{(l)}$  as  $l \rightarrow \infty$ . Let  $\{X(n), n \in \mathbf{Z}\}$  be the corresponding increasing shift  $a$ -selfsimilar additive random sequence. Then (4.28) is satisfied clearly by virtue of Lemma 4.1. Hence we see that

$$\int_0^\infty \mu_0([0, \varepsilon^{-1}ag(x)]) dx = \infty$$

and that

$$\int_0^\infty \mu_0([0, (ae)^{-1}g(x)]) dx \leq 1 + \sum_{k=1}^\infty \int_{b_{k-1}}^{b_k} \mu_0([0, e^{-1}g(x)]) \rho_1([0, g(x)]) dx$$

$$\leq 1 + 2 \sum_{k=1}^{\infty} e^{-M_k \log a} < \infty,$$

using (4.22) and noting  $M_{k+1} \geq M_k + 1$ . It follows from Corollary 4.1 that (4.18) holds for some  $c \in [(ae)^{-1}, \varepsilon^{-1}a]$  and hence (4.19) is true by replacing  $\{X(n), n \in \mathbf{Z}\}$  with  $\{c^{-1}X(n), n \in \mathbf{Z}\}$ .  $\square$

In the proof of the theorem above, we have proved the following corollary.

**Corollary 4.3.** *Let  $g(x) \in \mathcal{G}_0$ . Suppose that  $\rho_1(\{0\}) = 0$  and*

$$\liminf_{x \rightarrow \infty} \frac{-\log g(x)}{\log x} > 0.$$

*Then we have*

$$\liminf_{n \rightarrow \infty} \frac{X(n)}{a^n g(n)} = \infty \quad \text{a.s.}$$

**5. Rate of growth II**

In this section, let  $\{X(n), n \in \mathbf{Z}\}$  be an  $\mathbf{R}^d$ -valued non-zero shift  $a$ -self-similar additive random sequence for some  $a > 1$ . We study the rate of growth of  $\{X(n), n \in \mathbf{Z}\}$  in the “limsup” case. We state the results only as  $n \rightarrow \infty$  except in Remark 5.1. Define

$$\mathcal{G}_1 = \{g(x) : g(x) \text{ is positive and increasing on } [0, \infty)\}.$$

Define the inverse function  $g^{-1}(x)$  on  $[0, \infty)$  of  $g(x) \in \mathcal{G}_1$  as

$$g^{-1}(x) = \sup\{y \geq 0 : g(y) < x\}$$

with understanding that  $\sup \emptyset = 0$ . Define a function  $\rho_1^*(x)$  on  $[0, \infty)$  as

$$\rho_1^*(x) = P(|X(0) - X(-1)| > x).$$

A positive measurable function  $h(x)$  on  $[0, \infty)$  is said to be *submultiplicative* if there is a positive constant  $C_1$  such that

$$h(x + y) \leq C_1 h(x)h(y) \quad \text{for } \forall x, y \geq 0.$$

**Lemma 5.1.** *Let  $g(x) \in \mathcal{G}_1$  and let  $l \in \mathbf{N}$ . If*

$$\int_0^\infty P(|X(0) - X(-l)| > g(x)) dx = \infty,$$

then, for all  $k \in \mathbf{N}$  and all  $\varepsilon \in (0, 1)$ ,

$$\int_0^\infty P(|X(0) - X(-kl)| > (1 - \varepsilon)g(x)) dx = \infty.$$

Proof. Note that, for any  $j \in \mathbf{N}$ ,

$$(5.1) \quad \int_0^\infty P(|X(0) - X(-j)| > g(x)) dx = \int_{\mathbf{R}^d} g^{-1}(|x|)\rho_j(dx).$$

There are two cases. Case 1.  $M := \lim_{x \rightarrow \infty} g(x) < \infty$ ; Case 2.  $M = \infty$ . In Case 1,  $\rho_{kl}(\{x : |x| > (1 - \varepsilon)M\}) > 0$  for all  $k \in \mathbf{N}$  and all  $\varepsilon \in (0, 1)$  whenever  $\rho_l(\{x : |x| > (1 - \varepsilon)M\}) > 0$  for all  $\varepsilon \in (0, 1)$ . Hence we see from (5.1) that, if

$$\int_0^\infty P(|X(0) - X(-l)| > g(x)) dx = \infty,$$

then, for all  $k \in \mathbf{N}$  and all  $\varepsilon \in (0, 1)$ ,

$$\int_0^\infty P(|X(0) - X(-kl)| > (1 - \varepsilon)g(x)) dx = \infty.$$

In Case 2, we find from (5.1) that, if

$$\int_0^\infty P(|X(0) - X(-l)| > g(x)) dx = \infty,$$

then

$$\int_{\mathbf{R}^d} g^{-1}(|x|)\rho_l(dx) = \infty.$$

Choose  $N > 0$  such that  $\rho_l(\{x : |x| \leq N\}) > 0$ . We get, for all  $k \in \mathbf{N}$  and all  $\delta > 0$ , that

$$\begin{aligned} & \int_{\mathbf{R}^d} g^{-1}((1 + \delta)|x|)\rho_{kl}(dx) \\ &= \int_{(\mathbf{R}^d)^k} g^{-1} \left( (1 + \delta) \left| \sum_{n=0}^{k-1} a^{-nl} x_n \right| \right) \prod_{n=0}^{k-1} \rho_l(dx_n) \\ &\geq \{\rho_l(\{x : |x| \leq N\})\}^{k-1} \int_{\mathbf{R}^d} g^{-1}((1 + \delta)|x| - N(1 + \delta)(1 - a^{-l})^{-1})\rho_l(dx) \\ &\geq c_1 \int_{\mathbf{R}^d} g^{-1}(|x|)\rho_l(dx), \end{aligned}$$

where  $c_1$  is a positive constant. Note that we used the condition  $M = \infty$  in the last inequality. Thus the lemma is true from (5.1). □



**Lemma 5.2.** *Let  $g(x) \in \mathcal{G}_1$  and let  $l \in \mathbf{N}$ .*

(i) *If*

$$(5.2) \quad \int_0^\infty P(|X(0) - X(-l)| > g(x)) dx = \infty,$$

*then*

$$(5.3) \quad \limsup_{n \rightarrow \infty} \frac{|X(n)|}{a^n g(n)} \geq 1 \quad \text{a.s.}$$

(ii) *If*

$$(5.4) \quad \int_0^\infty P(|X(0) - X(-l)| > g(x)) dx < \infty,$$

*then*

$$(5.5) \quad \limsup_{n \rightarrow \infty} \frac{|X(n)|}{a^n g(n)} \leq (1 - a^{-l})^{-1} \quad \text{a.s.}$$

**Proof.** Suppose the condition (5.2) holds. That is,

$$\sum_{n=0}^{\infty} P(|X(0) - X(-l)| > g(n)) = \infty.$$

Then we see from the shift  $a$ -selfsimilarity that

$$\sum_{n=0}^{\infty} P(|X(n) - X(n-l)| > a^n g(n)) = \infty.$$

Hence there is  $j$  ( $0 \leq j \leq l-1$ ) such that

$$\sum_{n=0}^{\infty} P(|X(nl+j) - X((n-1)l+j)| > a^{nl+j} g(nl+j)) = \infty.$$

Define  $b_n = nl + j$  for  $n \in \mathbf{Z}$ . It follows from the Borel-Cantelli lemma that

$$P(|X(b_n) - X(b_{n-1})| > a^{b_n} g(b_n) \text{ i.o. as } n \rightarrow \infty) = 1.$$

Owing to Kolmogorov's 0-1 law, we see that

$$P\left(\limsup_{n \rightarrow \infty} \frac{|X(b_n)|}{a^{b_n} g(b_n)} \geq 1\right) = 0 \text{ or } 1.$$

If the probability above is 1, then (5.3) is true. Thus we can assume that the probability above is 0 and thereby we get

$$\limsup_{n \rightarrow \infty} \frac{|X(b_n)|}{a^{b_n} g(b_n)} < 1 \quad \text{a.s.}$$

and hence  $|X(b_{n-1})| < a^{b_{n-1}} g(b_{n-1})$  for all large  $n$  almost surely. Hence we obtain that

$$\begin{aligned} &P(|X(b_n)| > (1 - a^{-l})a^{b_n} g(b_n) \text{ i.o. as } n \rightarrow \infty) \\ &\geq P(|X(b_n) - X(b_{n-1})| > (1 - a^{-l})a^{b_n} g(b_n) + |X(b_{n-1})| \text{ i.o. as } n \rightarrow \infty) \\ &\geq P(|X(b_n) - X(b_{n-1})| > a^{b_n} g(b_n) \text{ i.o. as } n \rightarrow \infty) = 1. \end{aligned}$$

Thus we have

$$(5.6) \quad \limsup_{n \rightarrow \infty} \frac{|X(n)|}{a^n g(n)} \geq 1 - a^{-l} \quad \text{a.s.}$$

Hence we get (5.3) by using Lemma 5.1.

Suppose the condition (5.4) holds. Namely,

$$\sum_{n=0}^{\infty} P(|X(0) - X(-l)| > g(n)) < \infty.$$

Then we find from the shift  $a$ -selfsimilarity that

$$\sum_{n=0}^{\infty} P(|X(n) - X(n-l)| > a^n g(n)) < \infty.$$

It follows from the Borel-Cantelli lemma that there is  $N(\omega) \in \mathbf{Z}_+$  such that

$$(5.7) \quad P(|X(n) - X(n-l)| \leq a^n g(n) \text{ for } \forall n \geq N(\omega)) = 1.$$

Let  $n \geq N(\omega)$  and let  $m = m(\omega)$  be the largest integer satisfying  $n \geq ml + N(\omega)$ . We obtain from (5.7) that, for  $0 \leq j \leq m$ ,

$$(5.8) \quad |X(n - jl)| - |X(n - (j + 1)l)| \leq a^{n-jl} g(n - jl) \quad \text{a.s.}$$

Summing up (5.8) in  $j$ , we have

$$|X(n)| - |X(n - (m + 1)l)| \leq \sum_{j=0}^m a^{n-jl} g(n - jl) \leq \frac{a^n g(n)}{1 - a^{-l}} \quad \text{a.s.}$$

Hence we see that

$$\limsup_{n \rightarrow \infty} \frac{|X(n)|}{a^n g(n)} \leq \frac{1}{1 - a^{-l}} \quad \text{a.s.}$$

Thus we establish the inequality (5.5). □

**REMARK 5.1.** The assertions of the lemma above remain valid as  $n \rightarrow -\infty$ . However, we must replace  $a^{-l}$  by  $a_1^{-l}$  for some  $a_1 \in (1, a)$  in (5.5) and (5.6) as  $n \rightarrow -\infty$ . We need an analogue of Lemma 4.4 of [31], which is proved by virtue of (2.4).

**Theorem 5.1.** *Let  $g(x) \in \mathcal{G}_1$  and  $C \in [0, \infty]$ . Then*

$$(5.9) \quad \limsup_{n \rightarrow \infty} \frac{|X(n)|}{a^n g(n)} = C \quad \text{a.s.}$$

*if and only if*

$$(5.10) \quad \int_0^\infty P(|X(0) - X(-l)| > \delta g(x)) dx \begin{cases} = \infty & \text{for } 0 < \forall \delta < C \text{ and } \exists l(\delta) \in \mathbf{N} \\ < \infty & \text{for } \forall \delta > C \text{ and } \forall l \in \mathbf{N}. \end{cases}$$

*Thus, for every  $g(x) \in \mathcal{G}_1$ , there exists  $C \in [0, \infty]$  such that (5.9) holds.*

**Proof.** The proof is clear from Lemma 5.2. □

**Theorem 5.2.** *There exists  $g(x) \in \mathcal{G}_1$  satisfying*

$$(5.11) \quad \limsup_{n \rightarrow \infty} \frac{|X(n)|}{a^n g(n)} = 1 \quad \text{a.s.}$$

*if and only if  $\rho_1^*(x) \notin OR$ .*

**Proof.** Suppose that  $\rho_1^*(x) \in OR$  and there is  $g(x) \in \mathcal{G}_1$  satisfying (5.11). Then we see from Lemma 5.2 that

$$\int_0^\infty P(|X(0) - X(-1)| > 2^{-1}(1 - a^{-1})g(x)) dx = \infty$$

and

$$\int_0^\infty P(|X(0) - X(-1)| > 2g(x)) dx < \infty.$$

But they contradict the condition  $\rho_1^*(x) \in OR$ . Hence if  $\rho_1^*(x) \in OR$ , then there is no  $g(x) \in \mathcal{G}_1$  satisfying (5.11). Conversely, suppose that  $\rho_1^*(x) \notin OR$ . Then there is a positive sequence  $y_n \uparrow \infty$  for  $n \in \mathbf{Z}_+$  such that  $2^{-n}\rho_1^*(y_n) \geq \rho_1^*(2y_n)$  for  $n \in \mathbf{Z}_+$ . In

case  $M := \sup_{x \in S_{\rho_1}} |x| < \infty$ , we define  $g(x) \in \mathcal{G}_1$  as  $g(x) = M(1 - a^{-1})^{-1}$  on  $[0, \infty)$ . Then it is evident that

$$\sup_{x \in S_{\rho_1}} |x| = \frac{(1 - a^{-l})M}{1 - a^{-1}},$$

$$\int_0^\infty P(|X(0) - X(-l)| > g(x)) dx = 0 \quad \text{for } \forall l \geq 1$$

and

$$\int_0^\infty P(|X(0) - X(-l)| > (1 - a^{-l+1})g(x)) dx = \infty \quad \text{for } \forall l \geq 1.$$

Hence we see from Lemma 5.2 that (5.11) is true. In case  $M = \infty$ , we define  $g(x) \in \mathcal{G}_1$  together with  $x_n \uparrow \infty$  as  $x_0 = 0$  and  $g(x) = y_n$  on  $[x_n, x_{n+1})$  satisfying

$$1 \leq \rho_1^*(y_n)(x_{n+1} - x_n) \leq 2 \quad \text{for } n \in \mathbf{Z}_+.$$

Then we obtain that

$$\int_0^\infty P(|X(0) - X(-1)| > g(x)) dx = \sum_{n=0}^\infty \rho_1^*(y_n)(x_{n+1} - x_n) = \infty$$

and

$$\int_0^\infty P(|X(0) - X(-1)| > 2g(x)) dx \leq \sum_{n=0}^\infty 2^{-n} \rho_1^*(y_n)(x_{n+1} - x_n) < \infty.$$

It follows from Lemma 5.2 that there is  $C \in [1, 2(1 - a^{-1})^{-1}]$  satisfying (5.9). Thus we have (5.11) by replacing  $g(n)$  with  $Cg(n)$ . □

**Corollary 5.1.** *Let  $g(x) \in \mathcal{G}_1$ . Suppose that  $\rho_1^*(x) \in OR$ . If*

$$\int_0^\infty \rho_1^*(g(x)) dx < \infty \quad (\text{resp. } = \infty),$$

then

$$\limsup_{n \rightarrow \infty} \frac{|X(n)|}{a^n g(n)} = 0 \quad (\text{resp. } = \infty) \quad \text{a.s.}$$

Proof. Proof is clear from Lemma 5.2 and Theorem 5.2. □

As in Theorem 4.3, we fix  $a > 1$  and consider the family of all  $\mathbf{R}^d$ -valued shift  $a$ -selfsimilar additive random sequences  $\{X(n), n \in \mathbf{Z}\}$  in the following theorem.

**Theorem 5.3.** *Let  $g(x) \in \mathcal{G}_1$ . There exists  $\{X(n), n \in \mathbf{Z}\}$  satisfying (5.11) if and only if  $g^{-1}(x) + \log(1+x) \notin OR$ .*

*Proof.* We obtain from (5.1) that

$$(5.12) \quad \int_0^\infty \rho_1^*(g(x)) dx = \int_{\mathbf{R}^d} g^{-1}(|x|)\rho_1(dx).$$

Suppose that  $g^{-1}(x) + \log(1+x) \in OR$  and there is  $\{X(n), n \in \mathbf{Z}\}$  satisfying (5.11). By the same way as in the proof of the preceding theorem, we see from (5.12) that absurdity occurs. Thus if  $g^{-1}(x) + \log(1+x) \in OR$ , then there is no  $\{X(n), n \in \mathbf{Z}\}$  satisfying (5.11). Conversely, suppose that  $g^{-1}(x) + \log(1+x) \notin OR$ . In case  $g^{-1}(x)$  is not finite,  $M := \lim_{x \rightarrow \infty} g(x) < \infty$ . Let  $z = ((1 - a^{-1})M, 0, \dots, 0)' \in \mathbf{R}^d$ . Define  $\rho_1$  as  $\rho_1(\{0\}) = 1/2$  and  $\rho_1(\{z\}) = 1/2$ . Then we see as in the proof of Theorem 5.2 that (5.11) is true. Thus we can assume that  $g^{-1}(x)$  is finite on  $[0, \infty)$ . So there is  $x_n \uparrow \infty$  for  $n \in \mathbf{Z}_+$  such that  $x_0 = 1$  and  $2^{-n}(g^{-1}(x_n) + \log(1+x_n)) \geq g^{-1}(2^{-1}x_n) + \log(1+2^{-1}x_n)$  for  $n \in \mathbf{Z}_+$  and  $C_2 := \sum_{n=0}^\infty 1/(g^{-1}(x_n) + \log(1+x_n)) < \infty$ . Choose  $y_n \in \mathbf{R}^d$  for  $n \in \mathbf{Z}_+$  satisfying  $|y_n| = x_n$ . Define  $\rho_1$  as

$$\rho_1(\{y_n\}) = \frac{1}{C_2(g^{-1}(x_n) + \log(1+x_n))} \text{ and } \rho_1\left(\left(\bigcup_{n=0}^\infty \{y_n\}\right)^c\right) = 0.$$

Then we obtain that

$$\int_{\mathbf{R}^d} (g^{-1}(|x|) + \log(1+|x|))\rho_1(dx) = \sum_{n=0}^\infty C_2^{-1} = \infty$$

and

$$\begin{aligned} & \int_{\mathbf{R}^d} (g^{-1}(2^{-1}|x|) + \log(1+2^{-1}|x|))\rho_1(dx) \\ &= \sum_{n=0}^\infty \frac{g^{-1}(2^{-1}x_n) + \log(1+2^{-1}x_n)}{C_2(g^{-1}(x_n) + \log(1+x_n))} \leq C_2^{-1} \sum_{n=0}^\infty 2^{-n} < \infty. \end{aligned}$$

It follows from Theorem 5.1 and (5.12) that (5.10) holds for some  $C \in [1, 2(1 - a^{-1})^{-1}]$  and hence (5.11) is true by replacing  $\{X(n), n \in \mathbf{Z}\}$  with  $\{C^{-1}X(n), n \in \mathbf{Z}\}$ . □

**Corollary 5.2.** *Let  $g(x) \in \mathcal{G}_1$ . Suppose that  $g^{-1}(x) + \log(1+x) \in OR$ . If*

$$\int_{\mathbf{R}^d} g^{-1}(|x|)\rho_1(dx) < \infty \quad (\text{resp. } = \infty),$$

then

$$\limsup_{n \rightarrow \infty} \frac{|X(n)|}{a^n g(n)} = 0 \quad (\text{resp. } = \infty) \quad \text{a.s.}$$

Proof. Proof is evident from Lemma 5.2, Theorem 5.3 and (5.12). □

REMARK 5.2. We see from (2.4) and Corollary 5.2 that, for any  $\varepsilon > 0$ ,

$$\lim_{n \rightarrow \infty} \frac{|X(n)|}{(a + \varepsilon)^n} = 0 \quad \text{a.s.}$$

It follows from Remark 4.2 that, if  $\{X(n), n \in \mathbf{Z}\}$  is increasing and not zero, then

$$\lim_{n \rightarrow \infty} \frac{\log X(n)}{n} = \log a \quad \text{a.s.}$$

**Corollary 5.3.** *Let  $g(x) \in \mathcal{G}_1$  and  $C \in [0, \infty]$ . Suppose that  $g^{-1}(x)$  is finite and submultiplicative on  $[0, \infty)$ . Then (5.9) is true if and only if*

$$\int_{\mathbf{R}^d} g^{-1}(\delta|x|)\rho_1(dx) \begin{cases} < \infty & \text{for } 0 < \delta < C^{-1} \\ = \infty & \text{for } \delta > C^{-1}. \end{cases}$$

Proof. We prove that, for  $0 < \delta$ ,

$$(5.13) \quad \int_{\mathbf{R}^d} g^{-1}(\delta|x|)\rho_1(dx) < \infty \text{ implies } \int_{\mathbf{R}^d} g^{-1}(\delta|x|)\rho_l(dx) < \infty \text{ for } \forall l \geq 2.$$

We have, for  $l \geq 2$ ,

$$\begin{aligned} \int_{\mathbf{R}^d} g^{-1}(\delta|x|)\rho_l(dx) &= \int_{(\mathbf{R}^d)^l} g^{-1} \left( \delta \left| \sum_{n=0}^{l-1} a^{-n} x_n \right| \right) \prod_{n=0}^{l-1} \rho_1(dx_n) \\ &\leq c_1 \prod_{n=0}^{l-1} \int_{\mathbf{R}^d} g^{-1}(\delta a^{-n}|x_n|)\rho_1(dx_n) \\ &\leq c_1 \left\{ \int_{\mathbf{R}^d} g^{-1}(\delta|x|)\rho_1(dx) \right\}^l, \end{aligned}$$

where  $c_1$  is a positive constant. Thus (5.13) is true. Therefore the corollary follows from (5.1) and Theorem 5.1. □

REMARK 5.3. In the case where  $\rho_1$  is an infinitely divisible distribution on  $\mathbf{R}^d$ , we can replace  $\rho_1$  and  $\mathbf{R}^d$  by the Lévy measure of  $\rho_1$  and  $\{x : |x| > 1\}$ , respectively in the integral of Corollary 5.3. See Theorem 25.3 of [26].

### 6. Examples

In this section, we give some examples for the results in Sections 4 and 5. Let  $\{X(n), n \in \mathbf{Z}\}$  be an  $\mathbf{R}^d$ -valued non-zero shift  $a$ -self-similar additive random sequence for some  $a > 1$ . In Examples 6.1 and 6.2, we assume that  $d = 1$  and  $\{X(n), n \in \mathbf{Z}\}$  is increasing. More interesting examples will be found in [34].

EXAMPLE 6.1. Suppose that  $\rho_1(dx) = p\delta_0(dx) + (1-p)\delta_1(dx)$  with  $0 < p < 1$ . Denote  $\gamma = -\log p / \log a$ ,  $d_1 = (-p \log p - (1-p) \log(1-p)) / \log a$  and  $d_2 = \log 2 / \log a$ . Then  $\mu_n$  are called infinite Bernoulli convolutions with upper Hausdorff dimension  $d_1$  for  $a > p^{-p}(1-p)^{-(1-p)}$  and  $S_{\mu_n}$  are the Cantor sets with Hausdorff dimension  $d_2$  for  $a > 2$ .

(i) Let  $g(x) \in \mathcal{G}_0$ . If

$$\int_0^\infty \{g(x)\}^\gamma dx < \infty \quad (\text{resp. } = \infty),$$

then

$$\liminf_{n \rightarrow \pm\infty} \frac{X(n)}{a^n g(|n|)} = \infty \quad (\text{resp. } = 0) \quad \text{a.s.}$$

(ii) We have

$$\limsup_{n \rightarrow \pm\infty} \frac{X(n)}{a^n (1-a^{-1})^{-1}} = 1 \quad \text{a.s.}$$

Proof. Since we have

$$K_\lambda(x) = x^{-\gamma} \exp\left(-\int_1^x \frac{\log p - \log(p + (1-p)e^{-u})}{u \log a} du\right) \asymp x^{-\gamma},$$

the assertion (i) follows from Corollary 4.2. The assertion (ii) is essentially proved in the proof of Theorem 5.3. □

EXAMPLE 6.2. Let  $0 < \alpha < 1$  and let  $\xi(x)$  be a measurable function on  $[0, \infty)$  such that  $\lambda_1 \leq \xi(x) \leq \lambda_2$  on  $[0, \infty)$  and  $\lim_{x \downarrow 0} \xi(x) = \lambda_0$  for some positive constants  $\lambda_0, \lambda_1$ , and  $\lambda_2$ . Denote the constant  $C_\alpha$  as

$$C_\alpha = \left(\frac{1-\alpha}{\alpha}\right)^{(1-\alpha)/\alpha} \left(\frac{\Gamma(1-\alpha)\lambda_0}{1-a^{-\alpha}}\right)^{1/\alpha}.$$

Suppose that  $\rho_1$  is an infinitely divisible distribution on  $[0, \infty)$  given by

$$L_{\rho_1}(t) = \exp\left(\int_0^\infty (e^{-tx} - 1) \frac{\xi(x)}{x^{\alpha+1}} dx\right).$$

(i) We have

$$\liminf_{n \rightarrow \pm\infty} \frac{X(n)}{a^n (\log |n|)^{(\alpha-1)/\alpha}} = C_\alpha \quad \text{a.s.}$$

(ii) Let  $g(x) \in \mathcal{G}_1$ . If

$$\int_0^\infty \{g(x)\}^{-\alpha} dx < \infty \quad (\text{resp. } = \infty),$$

then

$$\limsup_{n \rightarrow \pm\infty} \frac{X(n)}{a^n g(|n|)} = 0 \quad (\text{resp. } = \infty) \quad \text{a.s.}$$

Proof. First we prove the assertion (i). We have

$$L_{\mu_0}(t) = \prod_{n=0}^{\infty} L_{\rho_1}(a^{-n}t) = \exp \left( \sum_{n=0}^{\infty} \int_0^\infty (e^{-tx} - 1) \frac{\xi(a^n x) a^{-n\alpha}}{x^{\alpha+1}} dx \right).$$

Note that

$$\lim_{x \downarrow 0} \sum_{n=0}^{\infty} \xi(a^n x) a^{-n\alpha} = \frac{\lambda_0}{1 - a^{-\alpha}}.$$

Hence we see from Theorem 8.2.2 of [2] that

$$(6.1) \quad -\log \mu_0 \left( \left[ 0, \frac{1}{t} \right] \right) \sim \frac{1-\alpha}{\alpha} \left( \frac{\Gamma(1-\alpha)\lambda_0}{1-a^{-\alpha}} \right)^{1/(1-\alpha)} t^{\alpha/(1-\alpha)} \quad \text{as } t \rightarrow \infty.$$

Define  $g(x) = (\log(x \vee e))^{-(1-\alpha)/\alpha}$ . Then  $g(x) \in \mathcal{G}_0$  and we obtain (4.18) from (6.1) with  $c = C_\alpha$ . It follows from Corollary 4.1 that the assertion (i) is true. Next we prove the assertion (ii). We see from Proposition 4.1 of [31] that  $\rho_1((x, \infty)) \in OR$  and  $\rho_1((x, \infty)) \asymp x^{-\alpha}$  as  $x \rightarrow \infty$ . Hence the assertion (ii) follows from Corollary 5.1.  $\square$

EXAMPLE 6.3. Let  $\alpha > 0$ . If

$$\int_{\mathbf{R}^d} |x|^\alpha \rho_1(dx) < \infty \quad (\text{resp. } = \infty),$$

then

$$\limsup_{n \rightarrow \pm\infty} \frac{|X(n)|}{a^n |n|^{1/\alpha}} = 0 \quad (\text{resp. } = \infty) \quad \text{a.s.}$$

Proof. Proof is clear from Corollary 5.2.  $\square$



EXAMPLE 6.4. Let  $\beta > 0$  and  $C \in [0, \infty]$ . Then we have

$$(6.2) \quad \limsup_{n \rightarrow \pm\infty} \frac{|X(n)|}{a^n (\log |n|)^{1/\beta}} = C \quad \text{a.s.}$$

if and only if

$$\int_{\mathbf{R}^d} \exp(\delta|x|^\beta) \rho_l(dx) \begin{cases} < \infty & \text{for } 0 < \forall \delta < C^{-\beta} \text{ and } \forall l \in \mathbf{N} \\ = \infty & \text{for } \forall \delta > C^{-\beta} \text{ and } \exists l(\delta) \in \mathbf{N}. \end{cases}$$

In the case where  $0 < \beta \leq 1$ , (6.2) holds if and only if

$$\int_{\mathbf{R}^d} \exp(\delta|x|^\beta) \rho_1(dx) \begin{cases} < \infty & \text{for } 0 < \delta < C^{-\beta} \\ = \infty & \text{for } \delta > C^{-\beta}. \end{cases}$$

Proof. Let  $g(x) = (\log(x \vee e))^{1/\beta}$  on  $[0, \infty)$ . Obviously,  $g(x) \in \mathcal{G}_1$  and  $g^{-1}(x) = \exp(x^\beta)$  on  $[1, \infty)$ . The first assertion is due to (5.1) and Theorem 5.1. Since  $g^{-1}(x)$  is submultiplicative on  $[0, \infty)$  for  $0 < \beta \leq 1$ , the second assertion follows from Corollary 5.3.  $\square$

REMARK 6.1. Let  $\{W(t), t \geq 0\}$  be a Brownian motion in  $\mathbf{R}^d$  and set  $X(n) = W(a^{2n})$  for  $n \in \mathbf{Z}$ . Then the equation (6.2) with  $\beta = 2$  and  $C = \sqrt{2}$  is a discrete analogue of the classical law of the iterated logarithm for the Brownian motion in  $\mathbf{R}^d$ .

ACKNOWLEDGEMENT. The author should like to express his thanks to Ken-iti Sato for his helpful advice. He is grateful to Makoto Maejima and Norio Kôno for their valuable comments and also thanks the referee for his careful suggestions.

---

### References

- [1] M.T. Barlow and E.A. Perkins: *Brownian motion on the Sierpinski gasket*, Probab. Theory Relat. Fields, **79** (1988), 543–624.
- [2] N.H. Bingham, C.M. Goldie and J.L. Teugels: *Regular Variation*, Cambridge University Press, Cambridge, 1987.
- [3] J. Bretagnolle and D. Dacunha-Castelle: *Théorèmes limites à distance finie pour les marches aléatoires*, Ann. Inst. Henri Poincaré, **4** (1968), 25–73.
- [4] J. Bunge: *Nested classes of C-decomposable laws*, Ann. Probab. **25** (1997), 215–229.
- [5] K.L. Chung and W.H. Fuchs: *On the distribution of values of sums of random variables*, Four Papers in Probability (Mem. Amer. Math. Soc., No. 6, Providence, RI.) (1951), 1–12.
- [6] B.E. Fristedt: *Sample function behavior of increasing processes with stationary, independent increments*, Pac. J. Math. **21** (1967), 21–33.
- [7] B.E. Fristedt and W.E. Pruitt: *Lower functions for increasing random walks and subordinators*, Z. Wahrsch. Verw. Gebiete, **18** (1971), 167–182.

- [8] L. de Haan and U. Stadtmüller: *Dominated variation and related concepts and Tauberian theorems for Laplace transform*, J. Math. Anal. Appl. **108** (1985), 344–365.
- [9] J. Hawkes: *Trees generated by a simple branching process*, J. London Math. Soc. **24** (1981), 373–384.
- [10] W.N. Hudson and J.D. Mason: *Operator-self-similar processes in a finite-dimensional space*, Trans. Amer. Math. Soc. **273** (1982), 281–297.
- [11] J.E. Hutchinson: *Fractals and self similarity*, Indiana Univ. Math. J. **30** (1981), 713–747.
- [12] R.G. Laha and V.K. Rohatgi: *Operator self-similar stochastic processes in  $R_d$* , Stoch. Proc. Appl. **12** (1982), 73–84.
- [13] J. Lamperti: *Semi-stable stochastic processes*, Trans. Amer. Math. Soc. **104** (1962), 62–78.
- [14] Q. Liu: *The exact Hausdorff dimension of a branching set*, Probab. Theory Relat. Fields **104** (1996), 515–538.
- [15] Q. Liu: *Exact packing measure on a Galton-Watson tree*, Stoch. Proc. Appl. **85** (2000), 19–28.
- [16] M. Loève: *Nouvelles classes de loi limites*, Bull. Soc. Math. France, **73** (1945), 107–126.
- [17] M. Maejima and Y. Naito: *Semi-selfdecomposable distributions and a new class of limit theorems*, Probab. Theory Relat. Fields, **112** (1998), 13–31.
- [18] M. Maejima and K. Sato: *Semi-selfsimilar processes*, J. Theoret. Probab. **12** (1999), 347–373.
- [19] M. Maejima, K. Sato and T. Watanabe: *Operator semi-selfdecomposability,  $(C, Q)$ -decomposability and related nested classes*, Tokyo J. Math. **22** (1999), 473–509.
- [20] D. Ornstein: *Random walks*, I and II, Trans. Amer. Math. Soc. **138** (1969), 1–43 and 45–60.
- [21] K.R. Parthasarathy: *Probability Measures on Metric Spaces*, Academic Press, 1967.
- [22] V.V. Petrov: *Sums of Independent Random Variables*, Springer, New York, 1975.
- [23] V.V. Petrov: *Limit Theorems of Probability Theory: Sequences of Independent Random Variables*, Oxford Univ. Press, 1995.
- [24] W.E. Pruitt: *The rate of escape of random walk*, Ann. Probab. **18** (1990), 1417–1461.
- [25] K. Sato: *Selfsimilar processes with independent increments*, Probab. Theory Relat. Fields, **89** (1991), 285–300.
- [26] K. Sato: *Lévy Processes and Infinitely Divisible Distributions*, Cambridge Univ. Press, 1999.
- [27] K. Sato and K. Yamamuro: *On selfsimilar and semi-selfsimilar processes with independent increments*, J. Korean Math. Soc. **35** (1998), 207–224.
- [28] K. Sato and M. Yamazato: *On distribution functions of class  $L$* , Z. Wahrsch. Verw. Gebiete, **43** (1978), 273–308.
- [29] F. Spitzer: *Principles of Random Walk*, Van Nostrand, Princeton, N. J., 1964.
- [30] C.J. Stone: *On the potential operator for one-dimensional recurrent random walks*, Trans. Amer. Math. Soc. **136** (1969), 413–426.
- [31] T. Watanabe: *Sample function behavior of increasing processes of class  $L$* , Probab. Theory Relat. Fields, **104** (1996), 349–374.
- [32] T. Watanabe: *Continuity properties of distributions with some decomposability*, J. Theoret. Probab. **13** (2000), 169–192.
- [33] T. Watanabe: *Absolute continuity of some semi-selfdecomposable distributions and selfsimilar measures*, Probab. Theory Relat. Fields, **117** (2000), 387–405.
- [34] T. Watanabe: *Shift selfsimilar additive random sequences associated with supercritical branching processes*, (2001) in J. Theoret. Probab., to appear.
- [35] S.J. Wolfe: *Continuity properties of decomposable probability measures on Euclidean spaces*, J. Multivar. Anal. **13** (1983), 534–538.
- [36] K. Yamamuro: *Transience conditions for self-similar additive processes*, J. Math. Soc. Japan, **52** (2000), 343–362.
- [37] K. Yamamuro: *On recurrence for self-similar additive processes*, Kodai Math. J. **23** (2000), 234–241.

Center for Mathematical Sciences  
The University of Aizu  
Aizu-Wakamatsu, 965-8580  
Japan