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ON THE RAJCHMAN PROPERTY FOR SELF-SIMILAR MEASURES

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Abstract

For classical Bernoulli convolutions, the convergence to zero at infinity of the Fourier transform was characterized by successive works of Erdős [3] and Salem [14]. We study this question for general self-similar measures.

1 Introduction

In the present article we consider the extension of some well-known results concerning Bernoulli convolutions to a more general context of self-similar measures. For a Borel probability measure μ on \mathbb{R} , define its Fourier transform as :

$$\hat{\mu}(t) = \int_{\mathbb{R}} e^{2i\pi tx} d\mu(x), \quad t \in \mathbb{R}.$$

We say that μ is Rajchman, if $\hat{\mu}(t) \rightarrow 0$, as $t \rightarrow +\infty$. In this study, starting in \mathbb{R} , Borel probability measures on $\mathbb{T} = \mathbb{R} \setminus \mathbb{Z}$ will naturally appear, quantifying the non-Rajchman character. If μ is a Borel probability measure on \mathbb{T} , its Fourier coefficients are :

$$\hat{\mu}(n) = \int_{\mathbb{T}} e^{2i\pi nx} d\mu(x), \quad n \in \mathbb{Z}.$$

For a Borel probability measure on \mathbb{R} , the Rajchman property holds for example if it has a density with respect to Lebesgue measure $\mathcal{L}_{\mathbb{R}}$, by the Riemann-Lebesgue lemma. However, it can be verified without density and for instance there exist Cantor sets of zero Lebesgue measure which support a Rajchman measure, cf Menshov [10]. Such questions on the Rajchman property of a measure naturally arise in Harmonic Analysis, for example when studying sets of multiplicity for trigonometric series, cf Lyons [9] or Zygmund [22]. We shall say a word on this topic at the end of the article. As a classical counter-example, mention the uniform measure μ on the standard triadic Cantor set, which is a singular continuous measure, not Rajchman (because $\hat{\mu}(3n) = \hat{\mu}(n)$, $n \in \mathbb{Z}$). The obstructions for a measure to be Rajchman are in general of arithmetical nature. The present work goes in this direction.

As it concerns $t \rightarrow +\infty$, the Rajchman character of a measure μ on \mathbb{R} is an information of local regularity. It says for example that μ has no atom; if it ever holds in a stronger form (fast enough decay), then μ has a density; etc. Stricto sensu, the regularity given by the Rajchman property is an equidistribution property modulo 1, since $\hat{\mu}(t) \rightarrow 0$ is equivalent to $\hat{\mu}(mt) \rightarrow 0$ for any integer $m \neq 0$. If X is a real random variable with law μ , then μ is Rajchman if and only if the law of tX mod 1 converges, as $t \rightarrow +\infty$, to Lebesgue measure $\mathcal{L}_{\mathbb{T}}$ on the torus $\mathbb{T} = \mathbb{R} \setminus \mathbb{Z}$.

Let us now recall standard notions on self-similar measures on the real line \mathbb{R} , with a probabilistic point of view. We write $\mathcal{L}(X)$ for the law of a real random variable X . Let $N \geq 0$ and real

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affine maps $\varphi_k(x) = r_k x + b_k$, with $r_k > 0$, for $0 \leq k \leq N$, and at least one $r_k < 1$. We call (C) the condition that the $(\varphi_k)_{0 \leq k \leq N}$ are all strict contractions, in other words :

$$(C) : \quad 0 < r_k < 1, \text{ for all } 0 \leq k \leq N.$$

Introduce the vectors $r = (r_k)_{0 \leq k \leq N}$ and $b = (b_k)_{0 \leq k \leq N}$. We notice for the sequel that for $n \geq 0$, a composition $\varphi_{k_{n-1}} \circ \dots \circ \varphi_{k_0}$ has the form :

$$\varphi_{k_{n-1}} \circ \dots \circ \varphi_{k_0}(x) = r_{k_{n-1}} \dots r_{k_0} x + \sum_{l=0}^{n-1} b_{k_l} r_{k_{n-1}} \dots r_{k_{l+1}}.$$

Consider the convex set $\mathcal{C}_N = \{p = (p_0, \dots, p_N) \mid p_i \geq 0, \sum_i p_i = 1\}$ and define :

$$\mathcal{D}_N(r) = \left\{ p \in \mathcal{C}_N \mid \sum_{0 \leq j \leq N} p_j \log r_j < 0 \right\}.$$

This is a non-empty open subset of \mathcal{C}_N , for the relative topology. Notice that $\mathcal{D}_N(r) = \mathcal{C}_N$, when condition (C) holds. Fixing a probability vector $p \in \mathcal{D}_N(r)$, we now compose the contractions at random, independently, according to p . Precisely, let X_0 be any real random variable and $(\varepsilon_n)_{n \geq 0}$ be independent and identically distributed random variables (*i.i.d.*), independent from X_0 , and with law p , in other words $\mathbb{P}(\varepsilon_n = k) = p_k$, $0 \leq k \leq N$. We consider the Markov chain $(X_n)_{n \geq 0}$ on \mathbb{R} defined by $X_n = \varphi_{\varepsilon_{n-1}} \circ \dots \circ \varphi_{\varepsilon_0}(X_0)$, $n \geq 0$.

The condition $p \in \mathcal{D}_N(r)$ is a hypothesis of contraction on average, rewritten as $\mathbb{E}(\log r_{\varepsilon_0}) < 0$. Classically, it implies that $(X_n)_{n \geq 0}$ has a unique invariant measure, written as ν . This for example follows from the fact that $\mathcal{L}(X_n) = \mathcal{L}(Y_n)$, where :

$$Y_n := \varphi_{\varepsilon_0} \circ \dots \circ \varphi_{\varepsilon_{n-1}}(X_0) = r_{\varepsilon_0} \dots r_{\varepsilon_{n-1}} X_0 + \sum_{l=0}^{n-1} b_{\varepsilon_l} r_{\varepsilon_0} \dots r_{\varepsilon_{l-1}}.$$

As a standard fact, (Y_n) is more stable than (X_n) . Using the Law of Large Numbers, we obtain $n^{-1} \log(r_{\varepsilon_0} \dots r_{\varepsilon_{n-1}}) \rightarrow \mathbb{E}(\log r_{\varepsilon_0}) < 0$, a.s., as $n \rightarrow +\infty$, so Y_n converges a.s., as $n \rightarrow +\infty$, to :

$$X := \sum_{l \geq 0} b_{\varepsilon_l} r_{\varepsilon_0} \dots r_{\varepsilon_{l-1}}.$$

Setting $\nu = \mathcal{L}(X)$, we obtain that $\mathcal{L}(X_n)$ weakly converges to ν . By construction, $\mathcal{L}(X_{n+1}) = \sum_{0 \leq j \leq N} p_j \mathcal{L}(X_n) \circ \varphi_j^{-1}$, hence, taking the limit as $n \rightarrow +\infty$, the measure ν verifies :

$$\nu = \sum_{0 \leq j \leq N} p_j \nu \circ \varphi_j^{-1}. \quad (1)$$

The previous convergence implies that the solution of this equation is unique among Borel probability measures. Moreover ν has to be of pure type, i.e. either purely atomic or absolutely continuous with respect to Lebesgue measure $\mathcal{L}_{\mathbb{R}}$ or else singular continuous, since each term in its Radon-Nikodym decomposition with respect to $\mathcal{L}_{\mathbb{R}}$ verifies (1). Let us now make a few remarks :

1) The measure ν is purely atomic if and only if the φ_j with $p_j > 0$ have a common fixed point c , in which case ν is the Dirac mass at c . Indeed (considering the necessity), suppose that ν has an atom. Let $a > 0$ be the maximal mass of an atom and E the finite set of points having mass a . Fixing any $c \in E$, the relation $\nu(\{c\}) = \sum_j p_j \nu(\{\varphi_j^{-1}(c)\})$ furnishes $\varphi_j^{-1}(c) \in E$, whenever $p_j > 0$. Hence $\varphi_j^{-n}(c) \in E$, $n \geq 0$. If $\varphi_j \neq id$, then $\varphi_j^{-1}(c) = c$, the set $\{\varphi_j^{-n}(c), n \geq 0\}$ being infinite otherwise. If $\varphi_j = id$, it fixes all points.

2) Let $f(x) = ax + b$ be an affine map, with $a \neq 0$. With the same $p \in \mathcal{C}_N$, the conjugate system $(\psi_j)_{0 \leq j \leq N}$, with $\psi_j = f \circ \varphi_j \circ f^{-1}$, has an invariant measure $w = \mathcal{L}(aX + b)$ and we have the relation $\hat{w}(t) = \hat{\nu}(at) e^{2i\pi tb}$. In particular ν is Rajchman if and only if w is Rajchman.

3) When supposing condition (C), some common self-similar set F can be introduced, where $F \subset \mathbb{R}$ is the unique non-empty compact set verifying the self-similarity relation :

$$F = \cup_{0 \leq k \leq N} \varphi_k(F).$$

See for example Hutchinson [5] for general properties of such sets. Introducing $\mathbb{N} = \{0, 1, \dots\}$ and the compact $S = \{0, \dots, N\}^{\mathbb{N}}$, condition (C) implies that F is a continuous image of S , in other words we have the following description :

$$F = \left\{ \sum_{l \geq 0} b_{x_l} r_{x_0} \cdots r_{x_{l-1}}, (x_0, x_1, \dots) \in S \right\}.$$

Under condition (C), the self-similar set F exists and supports any self-similar measures ν .

Let us return to the general case. We assume in the sequel that the φ_j with $p_j > 0$ do not have a common fixed point (in particular $N \geq 1$). A difficult problem is to characterize the absolute continuity of ν in terms of the parameters r , b and p . An example with a long and well-known history is that of Bernoulli convolutions, corresponding to $N = 1$, the affine contractions $\varphi_0(x) = \lambda x - 1$, $\varphi_1(x) = \lambda x + 1$, $0 < \lambda < 1$, and the probability vector $p = (1/2, 1/2)$. Notice that when the r_i are equal (to some real in $(0, 1)$), the situation is a little simplified, as ν is an infinite convolution (this is not true in general). Although we discuss below some works in this context, we will not present here the vast subject of Bernoulli convolutions, addressing the reader to detailed surveys, Peres-Schlag-Solomyak [12] or Solomyak [18].

For general self-similar measures, an important aspect of the problem, that we shall not enter, and an active line of research, concerns the Hausdorff dimension of the measure ν . In a large generality, cf for example Falconer [4] and more recently Jaroszevska and Rams [6], there is an ‘‘entropy/Lyapunov exponent’’ upper-bound :

$$\text{Dim}_{\mathcal{H}}(\nu) \leq \min\{1, s(p, r)\}, \text{ where } s(p, r) := \frac{-\sum_{i=0}^N p_i \log p_i}{-\sum_{i=0}^N p_i \log r_i}.$$

The quantity $s(p, r)$ is called the singularity dimension of the measure and can be > 1 . The equality $\text{Dim}_{\mathcal{H}}(\nu) = 1$ does not mean that ν is absolutely continuous, but the inequality $s(p, r) < 1$ implies that ν is singular. The interesting domain of parameters for the question of the absolute continuity of the invariant measure therefore corresponds to $s(p, r) \geq 1$.

We focus in this work on another fundamental tool, the Fourier transform $\hat{\nu}$. If ν is not Rajchman, the Riemann-Lebesgue lemma implies that ν is singular. This property was used by Erdős [3] in the context of Bernoulli convolutions. Erdős proved that if $1/2 < \lambda < 1$ is such that $1/\lambda$ is a Pisot number, then ν is not Rajchman. The reciprocal statement was next shown by Salem [14]. As a result, for Bernoulli convolutions the Rajchman property always holds, except for a very particular set of parameters. For general self-similar measures, under condition (C), the non-Rajchman character was recently shown to hold for only a very small set of parameters, by Solomyak [19] : if the $(\varphi_k)_{0 \leq k \leq N}$ do not have a common fixed point and $p \in \mathcal{C}_N$ is not degenerated, then outside a set of zero-Hausdorff dimension for r , the Fourier transform $\hat{\nu}$ even has a power decay at infinity.

Content of the article. The aim of the present article is to study for general self-similar measures the exceptional set where the Rajchman property is not true. We essentially show that the parameters r and b have to be very specific, as for Bernoulli convolutions. We shall first prove a general extension of the theorem of Salem [14], drastically reducing the set of parameters when the Rajchman property does not hold. Focusing then on this particular case and restricting to condition (C), we prove a partial extension of the theorem of Erdős [3]. We next give some complements, first rather surprising numerical simulations involving the Plastic number, then an application to sets of uniqueness for trigonometric series.

2 Statement of the results

Let us place in the general situation considered in the introduction. Certainly without surprise, Pisot numbers come out of the analysis, so let us introduce a few definitions. For notions concerning Algebraic Number Theory, we refer to Samuel [16].

Definition 2.1

A Pisot number is a real algebraic integer $\theta > 1$ with conjugates (the other roots of its minimal unitary polynomial) of modulus strictly less than 1. We fix such a $\theta > 1$, with minimal polynomial $Q \in \mathbb{Z}[X]$, of degree $s + 1$, with $s \geq 0$ (if $s = 0$, then θ is an integer ≥ 2). Then :

- For any $\alpha \in \mathbb{Q}[\theta]$, the trace $\text{Tr}(\alpha)$ is the trace of the linear operator $x \mapsto \alpha x$, from $\mathbb{Q}[\theta]$ to itself. Recall that $\text{Tr}(\alpha) \in \mathbb{Q}$.

- The set $\mathbb{Z}[\theta] = \mathbb{Z}\theta^0 + \dots + \mathbb{Z}\theta^s$ is a subring of the ring of algebraic integers of $\mathbb{Q}[\theta]$ and $\mathbb{Z}[\theta, 1/\theta]$ is the subring of $\mathbb{Q}[\theta]$ generated by θ and $1/\theta$. Let $\mathcal{D}(\theta)$ be the \mathbb{Z} -dual of $\mathbb{Z}[\theta]$, as a \mathbb{Z} -lattice, in other words $\mathcal{D}(\theta) = \{\alpha \in \mathbb{Q}[\theta], \text{Tr}(\theta^n \alpha) \in \mathbb{Z}, \text{ for } 0 \leq n \leq s\}$. It can be shown that $\mathcal{D}(\theta) = (1/Q'(\theta))\mathbb{Z}[\theta]$.

- Classically, $\text{Tr}(\theta^n \alpha) \in \mathbb{Z}$, for all $n \geq 0$, if this is true for $0 \leq n \leq s$. Let us introduce the following set, $\mathcal{T}(\theta) = \{\alpha \in \mathbb{Q}[\theta], \text{Tr}(\theta^n \alpha) \in \mathbb{Z}, \text{ for large } n \geq 0\}$. Then :

$$\mathcal{T}(\theta) = \cup_{n \geq 0} \theta^{-n} \mathcal{D}(\theta) = \frac{1}{Q'(\theta)} \mathbb{Z}[\theta, 1/\theta].$$

Let us now introduce particular families of affine contractions, somehow canonical (as we will see) for the analysis of the Rajchman property.

Definition 2.2

Let $N \geq 1$. A family of real affine maps $\varphi_k(x) = r_k x + b_k$, with $r_k > 0$, for $0 \leq k \leq N$, and at least one $r_k < 1$ and no common fixed point, is in reduced Pisot form, if there exist a Pisot number $1/\lambda > 1$, relatively prime integers $(n_k)_{0 \leq k \leq N}$ and $\mu_k \in \mathcal{T}(1/\lambda)$, $0 \leq k \leq N$, such that :

$$\varphi_j(x) = \lambda^{n_j} x + \mu_j, \text{ for all } 0 \leq j \leq N,$$

with moreover some Bezout relation $1 = \sum_{0 \leq j \leq N, n_j \neq 0} l_j n_j$ verifying the following centering :

$$0 = \sum_{0 \leq j \leq N, n_j \neq 0} \left(\frac{\mu_j}{1 - \lambda^{n_j}} \right) \lambda^{\sum_{0 \leq k < j, n_k \neq 0} l_k n_k} (1 - \lambda^{l_j n_j}).$$

We shall say that a Bezout centering relation is satisfied.

Remark. — If a family $(\varphi_j)_{0 \leq j \leq N}$ is in reduced Pisot form, there is unicity in its description. Indeed, supposing two, then for some $0 < \lambda, \lambda' < 1$ and all $0 \leq j \leq N$, we would have $\lambda^{n_j} = \lambda'^{m_j}$, with two families of relatively prime numbers $(n_j)_{0 \leq j \leq N}$ and $(m_j)_{0 \leq j \leq N}$. Taking some collection of integers (a_j) realizing a Bezout relation for the (n_j) , we would have :

$$\lambda = \lambda^{\sum_j a_j n_j} = \lambda'^{\sum_j a_j m_j} = \lambda'^p,$$

for some $p \geq 1$. Idem, $\lambda' = \lambda^q$, for some $q \geq 1$. Hence $pq = 1$, giving $p = q = 1$, $\lambda = \lambda'$ and $n_j = m_j$, for all $0 \leq j \leq N$. Notice finally that if some Bezout relation gives a centering as above, then another Bezout relation may not verify the same property.

As a first result (extending [14]), we shall show that if one wants to find some non-Rajchman invariant measure, it is necessary to consider families with such parameters.

Theorem 2.3

Let $N \geq 1$ and $p \in \mathcal{C}_N$, with $p_j > 0$, for all $0 \leq j \leq N$. Take affine maps $\varphi_k(x) = r_k x + b_k$, $r_k > 0$, for $0 \leq k \leq N$, with no common fixed point and such that $\sum_{0 \leq j \leq N} p_j \log r_j < 0$. Then the invariant measure ν is not Rajchman if and only if there exists $f(x) = ax + b$, $a \neq 0$, such that the conjugate system $(f \circ \varphi_j \circ f^{-1})_{0 \leq j \leq N}$ is in reduced Pisot form, for some Pisot number $1/\lambda > 1$, with invariant measure w verifying $\hat{w}(\lambda^{-k}) \not\rightarrow 0$, as $k \rightarrow +\infty$.

The last point of the theorem highlights the role of sequences of the form $(\alpha\lambda^{-k})_{k \geq 0}$, $\alpha \neq 0$, in the problem, as first considered in [3]. In a second step in the study of the non-Rajchman character, we now focus on families in reduced Pisot form.

Theorem 2.4

Let $N \geq 1$ and affine maps $\varphi_k(x) = \lambda^{n_k}x + \mu_k$, for $0 \leq k \leq N$, be in reduced Pisot form, with $1/\lambda > 1$ a Pisot number, relatively prime integers $(n_k)_{0 \leq k \leq N}$ and $\mu_k \in \mathcal{T}(1/\lambda)$, for $0 \leq k \leq N$, verifying a Bezout centering relation.

Let $p \in \mathcal{C}_N$ and denote by $(\varepsilon_n)_{n \in \mathbb{Z}}$ i.i.d. random variables, with $\mathbb{P}(\varepsilon_0 = k) = p_k$, $0 \leq k \leq N$, and such that $\mathbb{E}(n_{\varepsilon_0}) > 0$. Set $S_l = n_{\varepsilon_0} + \dots + n_{\varepsilon_{l-1}}$, $l \geq 1$, $S_0 = 0$ and $S_l = -n_{\varepsilon_l} - \dots - n_{\varepsilon_{l-1}}$, $l \leq -1$.

i) The random variable $X = \sum_{l \geq 0} \mu_{\varepsilon_l} \lambda^{S_l}$, with law ν , verifies that $\lambda^{-n}X \pmod 1$ converges in law, as $n \rightarrow +\infty$, to a probability measure m on \mathbb{T} , checking the invariance property :

$$\int_{\mathbb{T}} f(x) dm(x) = \frac{1}{\mathbb{E}(n_{\varepsilon_0})} \sum_{0 \leq r < n^*} \mathbb{E} \left[f \left(\sum_{l \in \mathbb{Z}} \mu_{\varepsilon_l} \lambda^{k+r+S_l} \right) \mathbf{1}_{\max_{u \geq 1} S_{-u} < -r} \right],$$

for all $f \in C(\mathbb{T}, \mathbb{R})$ and all $k \in \mathbb{Z}$, where $n^* = \max_{0 \leq k \leq N} n_k$.

ii) For $1 \leq \alpha \leq 1/\lambda$ such that $\alpha\mu_j \in \mathcal{T}(1/\lambda)$, for all $0 \leq j \leq N$, let m_α be the measure corresponding to m , when the $(\mu_j)_{0 \leq j \leq N}$ are replaced by the $(\alpha\mu_j)_{0 \leq j \leq N}$. Then ν is Rajchman if and only if $m_\alpha = \mathcal{L}_{\mathbb{T}}$, for any $1 \leq \alpha \leq 1/\lambda$ such that $\alpha\mu_j \in \mathcal{T}(1/\lambda)$, for all $0 \leq j \leq N$.

iii) Suppose that $n_j \geq 1$, for all $0 \leq j \leq N$. There exists $0 \neq a \in \mathbb{Z}$, depending only on λ , such that for any $k \neq 0$, then for all $p \in \mathcal{C}_N$ outside a finite set (depending on k), $\hat{m}(ak) \neq 0$. In particular :

- ν is not Rajchman, for any $p \in \mathcal{C}_N$ outside a finite set.
- ν is strongly non-Rajchman (i.e. $\hat{m}(ak) \neq 0$, $k \in \mathbb{Z}$), for all $p \in \mathcal{C}_N$ outside a countable set.

Remark. — Part iii) of Theorem 2.4 relies on a transversality method, based on the analysis of the regularity of $\hat{m}(n)$, for some fixed $n \in \mathbb{Z}$, as a function of $p \in \mathcal{C}_N$. We give very concrete examples in the last section, with $N = 1$ and $1/\lambda$ the Plastic number, where ν is not Rajchman for all $p \in \mathcal{C}_1$. On the existence of singular measures in the inhomogeneous case, we were previously essentially aware of the non-explicit examples, using algebraic curves, of Neunhuserer [11].

Remark. — Still on point iii) of Theorem 2.4, under condition (C), notice that when the Pisot number $1/\lambda$ is an integer ≥ 2 , then the involved finite set can be non-empty, since the invariant measure ν can have a density. For instance, if $N \geq 1$ and $\varphi_k(x) = (x+k)/(N+1)$, $0 \leq k \leq N$, with $p = (1/(N+1), \dots, 1/(N+1))$, then ν is Lebesgue measure on $[0, 1]$. In the general case and when the Pisot number $1/\lambda$ is irrational, we conjecture that $m \neq \mathcal{L}_{\mathbb{T}}$.

Remark. — Some number theoretic question appears in point ii) of Theorem 2.4. Fix a Pisot number $\theta > 1$ and a non-zero family $(\mu_j)_{0 \leq j \leq N} \in \mathcal{T}(\theta)^{N+1}$. Since $\theta^M \mu_j \in \mathcal{D}(\theta)$, for all $0 \leq j \leq N$, as soon as $M \geq 0$ is large enough, assume for example that $(\mu_j)_{0 \leq j \leq N} \in \mathcal{D}(\theta)^{N+1}$.

- For any $\mu \in \mathbb{Q}[\theta]$, define $den(\mu)$ as the lcm of the denominators of the vector of fractions $(Tr(\theta^l \mu))_{0 \leq l \leq s}$. Then $den(\mu)\mu \in \mathcal{D}(\theta)$. For $0 \neq \alpha \in \mathbb{Q}[\theta]$, then $q = \text{lcm}\{den(\alpha\mu_j), 0 \leq j \leq N\}$ is the smallest integer ≥ 1 such that $q\alpha\mu_j \in \mathcal{D}(\theta)$, for all $0 \leq j \leq N$.
- Another way is to take some other non-zero family $(\mu'_j)_{0 \leq j \leq N} \in \mathcal{D}(\theta)^{N+1}$. There exists $\alpha \neq 0$ (necessarily in $\mathbb{Q}[\theta]$) such that $\mu'_j = \alpha\mu_j$, for all $0 \leq j \leq N$, if and only if $\mu_i \mu'_j - \mu'_i \mu_j = 0$, for all $0 \leq i \neq j \leq N$. Since $\mathcal{D}(\theta) = (1/Q'(\theta))\mathbb{Z}[\theta]$, where $Q(x) = X^{s+1} + a_s X^s + \dots + a_0 \in \mathbb{Z}[X]$ is the minimal polynomial of θ , consider the equality $yz' - y'z = 0$, for elements y, y', z, z' in $\mathbb{Z}[\theta]$. Let $y = \sum_{0 \leq u \leq s} n_u \theta^u$ and $z = \sum_{0 \leq v \leq s} m_v \theta^v$, with similar expressions with ' for y' and z' . Introduce the integer-valued $(s+1) \times (s+1)$ -companion matrix M of Q :

$$M = \begin{pmatrix} 0 & 1 & \cdots & 0 \\ \vdots & \ddots & \ddots & \vdots \\ \vdots & \vdots & 0 & 1 \\ -a_0 & \cdots & -a_{s-1} & -a_s \end{pmatrix}.$$

If y has coordinates (n_0, \dots, n_s) in the basis $(\theta^0, \dots, \theta^s)$ of $\mathbb{Q}[\theta]$, then in the same basis θy has coordinates $(n_0, \dots, n_s)M$. From this it is not difficult to infer that the conditions on the $(n_u), (m_u), (n'_u), (m'_u)$ for the equality $yz' - y'z = 0$ can be reformulated as :

$$(n_0, \dots, n_s) \sum_{0 \leq u \leq s} m'_u M^u - (n'_0, \dots, n'_s) \sum_{0 \leq u \leq s} m_u M^u = 0.$$

In the same fashion, observe that for any $\mu \in \mathbb{Q}[\theta]$ and when setting $V = (Tr(\theta^0 \mu), \dots, Tr(\theta^s \mu))$, then $\mu \in \mathcal{T}(\theta)$ if and only if there exists $n \geq 0$ such that VM^n has integral entries.

3 Proof of Theorem 2.3

For the sequel, introduce *i.i.d.* random variables $(\varepsilon_n)_{n \geq 0}$ with law p , to which \mathbb{P} and \mathbb{E} refer. Recall that ν is the law of the random variable $\sum_{l \geq 0} b_{\varepsilon_l} r_{\varepsilon_0} \cdots r_{\varepsilon_{l-1}}$. Without loss of generality, we also assume that $0 < r_0 \leq r_1 \leq \dots \leq r_N$, with necessarily $r_0 < 1$.

Step 1. We prove that if $\log r_i / \log r_j \notin \mathbb{Q}$, for some $0 \leq i \neq j \leq N$, then ν is Rajchman. This was shown by Li and Sahlsten [8], under condition (C). In [8], some logarithmic decay at infinity of $\hat{\nu}$ is also proved, under an additional Diophantine condition.

For $n \geq 1$, consider the random walk $S_n = -\log r_{\varepsilon_0} - \dots - \log r_{\varepsilon_{n-1}}$, with $S_0 = 0$. For a real $s \geq 0$, introduce the finite stopping time $\tau_s = \min\{n \geq 0, S_n > s\}$ and write \mathcal{T}_s for the corresponding sub- σ -algebra of the underlying σ -algebra. Taking $\alpha > 0$ and $s \geq 0$:

$$\begin{aligned} \hat{\nu}(\alpha e^s) &= \mathbb{E} \left(e^{2\pi i \alpha e^s \sum_{l \geq 0} b_{\varepsilon_l} e^{-S_l}} \right) \\ &= \mathbb{E} \left(e^{2\pi i \alpha e^s \sum_{0 \leq l < \tau_s} b_{\varepsilon_l} e^{-S_l}} e^{2\pi i \alpha e^{-S_{\tau_s} + s} \sum_{l \geq \tau_s} b_{\varepsilon_l} e^{-S_l + S_{\tau_s}}} \right). \end{aligned}$$

In the expectation, the first exponential term is \mathcal{T}_s -measurable. Also, the conditional expectation of the second exponential term with respect to \mathcal{T}_s is just $\hat{\nu}(\alpha e^{-S_{\tau_s} + s})$, as a consequence of the strong Markov property. It follows that :

$$\hat{\nu}(\alpha e^s) = \mathbb{E} \left(\hat{\nu}(\alpha e^{-S_{\tau_s} + s}) e^{2\pi i \alpha e^s \sum_{0 \leq l < \tau_s} b_{\varepsilon_l} e^{-S_l}} \right).$$

This gives $|\hat{\nu}(\alpha e^s)| \leq \mathbb{E} (|\hat{\nu}(\alpha e^{-S_{\tau_s} + s})|)$, so by the Cauchy-Schwarz inequality and a safe Fubini theorem consecutively :

$$\begin{aligned} |\hat{\nu}(\alpha e^s)|^2 &\leq \mathbb{E} (|\hat{\nu}(\alpha e^{-S_{\tau_s} + s})|^2) = \mathbb{E} \left(\int_{\mathbb{R}^2} e^{2\pi i \alpha e^{-S_{\tau_s} + s} (x-y)} d\nu(x) d\nu(y) \right) \\ &= \int_{\mathbb{R}^2} \mathbb{E} \left(e^{2\pi i \alpha e^{-S_{\tau_s} + s} (x-y)} \right) d\nu(x) d\nu(y). \end{aligned}$$

Let $Y := -\log r_{\varepsilon_0}$. As the law of Y is non-lattice (since some $\log r_i / \log r_j \notin \mathbb{Q}$ and $p_k > 0$ for all $0 \leq k \leq N$) and with $0 < \mathbb{E}(Y) < \infty$, it is a well-known consequence of the Blackwell theorem on the law of the overshoot that (see for instance Woodroffe [21], chap. 2, thm 2.3), that :

$$\mathbb{E}(g(S_{\tau_s} - s)) \rightarrow \frac{1}{\mathbb{E}(S_{\tau_0})} \int_0^{+\infty} g(x) \mathbb{P}(S_{\tau_0} > x) dx, \text{ as } s \rightarrow +\infty,$$

for any Riemann-integrable g . Notice for the sequel that S_{τ_0} has support in some $[0, A]$, so $\mathbb{P}(S_{\tau_0} > x) = 0$ for large $x > 0$. By dominated convergence, for any $\alpha > 0$:

$$\limsup_{t \rightarrow +\infty} |\hat{\nu}(t)|^2 \leq \frac{1}{\mathbb{E}(S_{\tau_0})} \int_{\mathbb{R}^2} \left| \int_0^{+\infty} e^{2\pi i \alpha e^{-u} (x-y)} \mathbb{P}(S_{\tau_0} > u) du \right| d\nu(x) d\nu(y).$$

The inside term (in the modulus) is uniformly bounded with respect to $(x, y) \in \mathbb{R}^2$. We shall use dominated convergence once more, this time with $\alpha \rightarrow +\infty$. It is sufficient to show that for $\nu^{\otimes 2}$ -almost every (x, y) , the inside term goes to zero. Since ν is non-atomic, $\nu^{\otimes 2}$ -almost-surely, $x \neq y$. If for example $x > y$:

$$\int_0^{+\infty} e^{2\pi i \alpha e^{-u}(x-y)} \mathbb{P}(S_{\tau_0} > u) du = \int_0^{x-y} e^{2\pi i \alpha t} \mathbb{P}(S_{\tau_0} > \log((x-y)/t)) \frac{dt}{t},$$

making the change of variable $t = e^{-u}(x-y)$. Remark that the integrated term is zero for small enough $t > 0$. The integral now converges to 0, as $\alpha \rightarrow +\infty$, by the Riemann-Lebesgue lemma. This shows that $\lim_{t \rightarrow +\infty} \hat{\nu}(t) = 0$ and completes the proof of this step.

Step 2. From *Step 1*, if ν is not Rajchman, then $\log r_i / \log r_j \in \mathbb{Q}$, for all (i, j) , hence $r_j = r_0^{p_j/q_j}$, with integers $p_j \in \mathbb{Z}$, $q_j \geq 1$, for $1 \leq j \leq N$. Let :

$$n_0 = \prod_{1 \leq l \leq N} q_l \geq 1 \text{ and } n_j = p_j \prod_{1 \leq l \leq N, l \neq j} q_l \in \mathbb{Z}, \quad 1 \leq j \leq N.$$

Setting $\lambda = r_0^{1/n_0} \in (0, 1)$, one has $r_j = \lambda^{n_j}$, $0 \leq j \leq N$. Up to taking some positive integer power of λ , one can assume that $\gcd(n_0, \dots, n_N) = 1$. Recall in passing that the set of Pisot numbers is stable under positive powers. Notice that the condition $\mathbb{E}(\log r_{\varepsilon_0}) < 0$ becomes $\mathbb{E}(n_{\varepsilon_0}) > 0$. We also have $n_N \leq \dots \leq n_0$, with $n_0 \geq 1$.

Using now some sub-harmonicity, one can reinforce the assumption that $\hat{\nu}(t)$ is not converging to 0, as $t \rightarrow +\infty$.

Lemma 3.1

There exists $1 \leq \alpha \leq 1/\lambda$ and $c > 0$ such that $\hat{\nu}(\alpha \lambda^{-k}) = c_k e^{2i\pi\theta_k}$, written in polar form, verifies $c_k \rightarrow c$, as $k \rightarrow +\infty$.

Proof of the lemma :

Let us write this time $S_n = n_{\varepsilon_0} + \dots + n_{\varepsilon_{n-1}}$, for $n \geq 1$, with $S_0 = 0$. Since $\mathbb{E}(n_{\varepsilon_0}) > 0$, (S_n) is transient to $+\infty$. Introduce the random ladder epochs $0 = \sigma_0 < \sigma_1 < \dots$, where inductively σ_{k+1} is the first time $n \geq 0$ with $S_n > S_{\sigma_k}$. Let $S'_k = S_{\sigma_k}$. The $(S'_k - S'_{k-1})_{k \geq 1}$ are *i.i.d.* random variables with law $\mathcal{L}(S_{\tau_0})$ and support in $\{1, \dots, n_0\}$. Since $\gcd(n_0, \dots, n_N) = 1$, the support of the law of S_{τ_0} generates \mathbb{Z} as an additive group (cf for example Woodroffe [21], thm 2.3, second part). For an integer $u \geq 1$ large enough, we can fix integers $r \geq 1$ and $s \geq 1$ such that the support of the law of S'_r contains u and that of S'_s contains $u+1$, both supports being included in some $\{1, \dots, M\}$, with therefore $1 \leq u \leq u+1 \leq M$. Proceeding as in *Step 1*, for any $t \in \mathbb{R}$:

$$\hat{\nu}(t) = \mathbb{E} \left(e^{2\pi i t \sum_{l \geq 0} b_{\varepsilon_l} \lambda^{S_l}} \right) = \mathbb{E} \left(\hat{\nu}(t \lambda^{S'_r}) e^{2\pi i t \sum_{0 \leq l < \sigma_r} b_{\varepsilon_l} \lambda^{S_l}} \right).$$

Doing the same thing with S'_s then gives :

$$|\hat{\nu}(t)| \leq \mathbb{E} \left(|\hat{\nu}(t \lambda^{S'_r})| \right) \text{ and } |\hat{\nu}(t)| \leq \mathbb{E} \left(|\hat{\nu}(t \lambda^{S'_s})| \right). \quad (2)$$

In particular, $|\hat{\nu}(t)| \leq \max_{1 \leq l \leq M} |\hat{\nu}(\lambda^l t)|$. We now set :

$$V_\alpha(k) := \max_{k \leq l < k+M} |\hat{\nu}(\alpha \lambda^l)|, \quad k \in \mathbb{Z}, \quad \alpha > 0.$$

The previous remarks imply that $V_\alpha(k) \leq V_\alpha(k+1)$, $k \in \mathbb{Z}$, $\alpha > 0$.

Since ν is not Rajchman, $|\hat{\nu}(t_l)| \geq c' > 0$, along some sequence $t_l \rightarrow +\infty$. Write $t_l = \alpha_l \lambda^{-k_l}$, with $1 \leq \alpha_l \leq 1/\lambda$ and $k_l \rightarrow +\infty$. Up to taking a subsequence, $\alpha_l \rightarrow \alpha \in [1, 1/\lambda]$. Fixing $k \in \mathbb{Z}$:

$$c' \leq V_{\alpha_l}(-k_l) \leq V_{\alpha_l}(-k),$$

as soon as l is large enough. By continuity, letting $l \rightarrow +\infty$, we get $c' \leq V_\alpha(-k)$, $k \in \mathbb{Z}$. As $k \mapsto V_\alpha(-k)$ is non-increasing, $V_\alpha(-k) \rightarrow c \geq c'$, as $k \rightarrow +\infty$. We now show that necessarily $|\hat{\nu}(\alpha\lambda^{-k})| \rightarrow c$, as $k \rightarrow +\infty$.

If this were not true, there would exist $\varepsilon > 0$ and $(m_k) \rightarrow +\infty$, with $|\hat{\nu}(\alpha\lambda^{-m_k})| \leq c - \varepsilon$. Since $V_\alpha(-k) \rightarrow c$ and $|\hat{\nu}(\alpha\lambda^{-m_k})| \leq c - \varepsilon$, as $k \rightarrow +\infty$, consider (2) with r and $t = \alpha\lambda^{-m_k - u}$ and next with s and $t = \alpha\lambda^{-m_k - u - 1}$. Since u is in the support of the law of S'_r and $u + 1$ in the support of the law of S'_s , we obtain the existence of some $c_1 < c$ such that for k large enough :

$$\max\{|\hat{\nu}(\alpha\lambda^{-m_k - u})|, |\hat{\nu}(\alpha\lambda^{-m_k - u - 1})|\} \leq c_1 < c.$$

Again via (2), with successively r and $t = \alpha\lambda^{-m_k - 2u}$, next r and $t = \alpha\lambda^{-m_k - 2u - 1}$ and finally s and $t = \alpha\lambda^{-m_k - 2u - 2}$, still using that u is in the support of the law of S'_r and $u + 1$ in the support of the law of S'_s , we get some $c_2 < c$ such that for k large enough :

$$\max\{|\hat{\nu}(\alpha\lambda^{-m_k - 2u})|, |\hat{\nu}(\alpha\lambda^{-m_k - 2u - 1})|, |\hat{\nu}(\alpha\lambda^{-m_k - 2u - 2})|\} \leq c_2 < c.$$

Etc, for some $c_{M-1} < c$ and k large enough :

$$\max\{|\hat{\nu}(\alpha\lambda^{-m_k - (M-1)u})|, \dots, |\hat{\nu}(\alpha\lambda^{-m_k - (M-1)u - (M-1)})|\} \leq c_{M-1} < c.$$

This contradicts the fact that $V_\alpha(-k) \rightarrow c$, as $k \rightarrow \infty$. We conclude that $|\hat{\nu}(\alpha\lambda^{-k})| \rightarrow c$, as $k \rightarrow \infty$, and this ends the proof of the lemma. \square

Step 3. We complete the proof of Theorem 2.3. In this part, introduce the notation $\|x\| = \text{dist}(x, \mathbb{Z})$, for $x \in \mathbb{R}$. Let us consider any $1 \leq \alpha \leq 1/\lambda$, with $\hat{\nu}(\alpha\lambda^{-k}) = c_k e^{2i\pi\theta_k}$, verifying $c_k \rightarrow c > 0$, as $k \rightarrow +\infty$. We start from the relation :

$$\hat{\nu}(\alpha\lambda^{-k}) = \sum_{0 \leq j \leq N} p_j e^{2i\pi\alpha\lambda^{-k}b_j} \hat{\nu}(\alpha\lambda^{-k+n_j}),$$

obtained by conditioning with respect to the value of n_{ε_0} . This furnishes for $k \geq 0$:

$$c_k = \sum_{0 \leq j \leq N} p_j e^{2i\pi(\alpha\lambda^{-k}b_j + \theta_{k-n_j} - \theta_k)} c_{k-n_j}.$$

We rewrite this as :

$$\sum_{0 \leq j \leq N} p_j \left[e^{2i\pi(\alpha\lambda^{-k}b_j + \theta_{k-n_j} - \theta_k)} - 1 \right] c_{k-n_j} = c_k - \sum_{0 \leq j \leq N} p_j c_{k-n_j} = \sum_{0 \leq j \leq N} p_j (c_k - c_{k-n_j}).$$

Let $K > 0$ be such that $c_{k-n_j} \geq c/2 > 0$, for $k \geq K$ and all $0 \leq j \leq N$. For $L > n^*$, where $n^* = \max_{0 \leq j \leq N} |n_j|$, we sum the previous equality on $K \leq k \leq K + L$:

$$\sum_{0 \leq j \leq N} p_j \sum_{k=K}^{K+L} c_{k-n_j} \left[e^{2i\pi(\alpha\lambda^{-k}b_j + \theta_{k-n_j} - \theta_k)} - 1 \right] = \sum_{0 \leq j \leq N} p_j \left(\sum_{k=K}^{K+L} c_k - \sum_{k=K-n_j}^{K+L-n_j} c_k \right).$$

Observe that the right-hand side involves a telescopic sum and is bounded by $2n^*$ (using that $|c_k| \leq 1$), uniformly in K and L . In the left hand-hand side, we take the real part and use that $1 - \cos(2\pi x) = 2(\sin \pi x)^2$, which, as is well-known, has the same order as $\|x\|^2$. We obtain, for some constant C , that for K and L large enough :

$$\frac{c}{2} \sum_{0 \leq j \leq N} p_j \sum_{k=K}^{K+L} \|\alpha\lambda^{-k}b_j + \theta_{k-n_j} - \theta_k\|^2 \leq C.$$

Introducing the constants $p_* = \min_{0 \leq j \leq N} p_j > 0$ and $C' = 2C/(cp_*)$, we get that for all $0 \leq j \leq N$ and K, L large enough :

$$\sum_{k=K}^{K+L} \|\alpha \lambda^{-k} b_j + \theta_{k-n_j} - \theta_k\|^2 \leq C'. \quad (3)$$

In the sequel, we distinguish two cases : there is a non-zero translation (case 1) or not (case 2).

- *Case 1.* For any non-zero-translation $\varphi_j(x) = x + b_j$, we have $n_j = 0$ and $b_j \neq 0$. Then (3) gives that for K, L large enough :

$$\sum_{k=K}^{K+L} \|\alpha \lambda^{-k} b_j\|^2 \leq C'.$$

This implies that $(\|\alpha b_j \lambda^{-k}\|)_{k \geq 0} \in l^2(\mathbb{N})$. By a classical theorem of Pisot, cf Cassels [2], chap. 8, Theorems I and II, we obtain that $1/\lambda$ is a Pisot number and $b_j = (1/\alpha)\mu_j$, with $\mu_j \in \mathcal{T}(1/\lambda)$. Consider now the non-translations $\varphi_j(x) = \lambda^{n_j}x + b_j$, $n_j \neq 0$. By (3), for any $r \geq 0$ and K, L large enough (depending on r) :

$$\sum_{k=K}^{K+L} \|\alpha \lambda^{-k+r n_j} b_j + \theta_{k-(r+1)n_j} - \theta_{k-r n_j}\|^2 \leq C'.$$

Fixing $l_j \geq 1$ and summing over $0 \leq r \leq l_j - 1$, making use of the triangular inequality and of $(x_1 + \dots + x_n)^2 \leq n(x_1^2 + \dots + x_n^2)$, we obtain, for K, L large enough (depending on l_j) :

$$\sum_{k=K}^{K+L} \left\| \alpha \lambda^{-k} b_j \left(\frac{1 - \lambda^{l_j n_j}}{1 - \lambda^{n_j}} \right) + \theta_{k-l_j n_j} - \theta_k \right\|^2 \leq l_j C'. \quad (4)$$

Changing k into $k + l_j n_j$, we obtain, for K, L large enough (depending on l_j) :

$$\sum_{k=K}^{K+L} \left\| \alpha \lambda^{-k} b_j \left(\frac{1 - \lambda^{-l_j n_j}}{1 - \lambda^{n_j}} \right) + \theta_{k+l_j n_j} - \theta_k \right\|^2 \leq l_j C'. \quad (5)$$

Let $1 = \sum_{0 \leq j \leq N} l_j n_j$ be a Bezout relation and $J \subset \{0, \dots, N\}$ be the subset where $l_j n_j \neq 0$, equipped with its natural order. Using successively for $j \in J$ either (4) or (5), according to the sign of l_j , we obtain with :

$$b = \sum_{j \in J} b_j \lambda^{\sum_{k \in J, k < j} l_k n_k} \left(\frac{1 - \lambda^{l_j n_j}}{1 - \lambda^{n_j}} \right), \quad (6)$$

the following relation, for a new constant C' and all K, L large enough :

$$\sum_{k=K}^{K+L} \|\alpha \lambda^{-k} b + \theta_{k-1} - \theta_k\|^2 \leq C'.$$

Now, for any $n_j \neq 0$, whatever the sign of n_j is, we arrive at, for some constant C' and all K, L large enough :

$$\sum_{k=K}^{K+L} \|\alpha \lambda^{-k} b \left(\frac{1 - \lambda^{n_j}}{1 - \lambda} \right) + \theta_{k-n_j} - \theta_k\|^2 \leq C'.$$

Hence, setting $b' = b/(1 - \lambda)$, for any $0 \leq j \leq N$ with $n_j \neq 0$, for some new constant C' and all K, L large enough, using (3) :

$$\sum_{k=K}^{K+L} \|\alpha \lambda^{-k} (b_j - b'(1 - \lambda^{n_j}))\|^2 \leq C'.$$

Let $0 \leq j \leq N$ with $n_j \neq 0$. If $b_j \neq b'(1 - \lambda^{n_j})$, then we deduce again that $1/\lambda$ is a Pisot number and $b_j = b'(1 - \lambda^{n_j}) + (1/\alpha)\mu_j$, with $\mu_j \in \mathcal{T}(1/\lambda)$. The other case is $b_j = b'(1 - \lambda^{n_j})$. In any case, we deduce that for all $0 \leq j \leq N$:

$$\varphi_j(x) = b' + \lambda^{n_j}(x - b') + (1/\alpha)\mu_j, \quad (7)$$

for some $\mu_j \in \mathcal{T}(1/\lambda)$. Finally, remark that (7) says that the $(\varphi_j)_{0 \leq j \leq N}$ are conjugated with the $(\psi_j)_{0 \leq j \leq N}$, where $\psi_j(x) = \lambda^{n_j}x + \mu_j$.

- *Case 2.* Then any φ_j with $n_j = 0$ is the identity. The conclusion is the same, because there now necessarily exists some $0 \leq j \leq N$ with $n_j \neq 0$ and $b_j \neq b'(1 - \lambda^{n_j})$, otherwise b' is a common fixed point for all $(\varphi_j)_{0 \leq j \leq N}$.

Let us finally check the centering relation. From relation (6), injecting the value of each $b_j = b(1 - \lambda^{n_j})/(1 - \lambda) + (1/\alpha)\mu_j$, we get a telescopic sum and it is immediate that the $(\mu_j)_{0 \leq j \leq N}$ are centered. Reciprocally, if starting from a centered family $(b_j)_{0 \leq j \leq N}$, one can choose the Bezout relation giving the centering. This gives in this case $b = b' = 0$, so $b_j = (1/\alpha)\mu_j$, for all $0 \leq j \leq N$.

This ends the proof of the theorem and shows half of *ii*) in Theorem 2.4. \square

4 Proof of Theorem 2.4

Let $N \geq 1$ and affine maps $\varphi_k(x) = \lambda^{n_k}x + \mu_k$, for $0 \leq k \leq N$, in reduced Pisot form, with $1/\lambda > 1$ a Pisot number, relatively prime integers $(n_k)_{0 \leq k \leq N}$ and $\mu_k \in \mathcal{T}(1/\lambda)$, for $0 \leq k \leq N$, verifying a centering relation. Let $p \in \mathcal{C}_N$ and denote by $(\varepsilon_n)_{n \in \mathbb{Z}}$ *i.i.d.* random variables with law p , to which the probability \mathbb{P} and the expectation \mathbb{E} refer. We suppose that $\mathbb{E}(n_{\varepsilon_0}) > 0$. Without loss of generality, we also assume that $n_N \leq \dots \leq n_0$, with $n_0 \geq 1$. For general background on Markov chains, we refer to Spitzer [20].

Recall the cocycle notations introduced in the statement of the theorem and denote by θ the formal shift such that $\theta\varepsilon_l = \varepsilon_{l+1}$, $l \in \mathbb{Z}$. We have for all k and l in \mathbb{Z} :

$$S_{k+l} = S_k + \theta^k S_l.$$

Recall that ν is the law of $X = \sum_{l \geq 0} \mu_{\varepsilon_l} \lambda^{S_l}$. We write $Q \in \mathbb{Z}[X]$ for the minimal polynomial of $1/\lambda$, of degree $s + 1$, with roots $\alpha_0 = 1/\lambda$, $\alpha_1, \dots, \alpha_s$, where $|\alpha_k| < 1$, for $1 \leq k \leq s$. Recall that the case $s = 0$ corresponds to $1/\lambda$ an integer ≥ 2 (using then usual conventions regarding sums or products). When $\mu \in \mathcal{T}(1/\lambda)$ and $k \geq 0$ is large enough, we have :

$$\lambda^{-k}\mu + \sum_{1 \leq j \leq s} \alpha_j^k \mu^{(j)} = \text{Tr}(\lambda^{-k}\mu) \in \mathbb{Z},$$

where the $(\mu^{(j)})_{1 \leq j \leq s}$ are the conjugates of μ (in the field $\mathbb{Q}[1/\lambda]$). This ensures that for any $k \in \mathbb{Z}$, the random variable $\sum_{l \in \mathbb{Z}} \mu_{\varepsilon_l} \lambda^{-k+S_l} \pmod{1}$ is a well-defined element of \mathbb{T} .

Step 1. Since $\sum_{l < 0} \mu_{\varepsilon_l} \lambda^{-n+S_l} \pmod{1}$ converges almost-surely to 0 in \mathbb{T} , as $n \rightarrow +\infty$, we just need to study the convergence in law of $\sum_{l \in \mathbb{Z}} \mu_{\varepsilon_l} \lambda^{-n+S_l} \pmod{1}$, as $n \rightarrow +\infty$. In order to consider the convergence with $f \in C(\mathbb{T}, \mathbb{R})$, it is enough to consider the case of any $e^{2i\pi mx}$. Let $k \in \mathbb{Z}$ be a fixed integer and $m \neq 0$ an integer. Looking at $(S_l)_{l \in \mathbb{Z}}$ and the first $q \in \mathbb{Z}$ such that $S_q \geq n$, we have :

$$\begin{aligned} \mathbb{E} \left(e^{2i\pi m \sum_{l \in \mathbb{Z}} \mu_{\varepsilon_l} \lambda^{k-n+S_l}} \right) &= \sum_{0 \leq r < n_0} \sum_{q \in \mathbb{Z}} \mathbb{E} \left(e^{2i\pi m \sum_{l \in \mathbb{Z}} \mu_{\varepsilon_l} \lambda^{(k-n+S_q)+(S_l-S_q)}} \mathbf{1}_{S_{q-u} < n, u \geq 1, S_q = n+r} \right) \\ &= \sum_{0 \leq r < n_0} \sum_{q \in \mathbb{Z}} \mathbb{E} \left(e^{2i\pi m \sum_{l \in \mathbb{Z}} \mu_{\varepsilon_l} \lambda^{k+r+\theta^q S_{l-q}}} \mathbf{1}_{\theta^q S_{-u} < -r, u \geq 1, \theta^q S_{-q} = -n-r} \right) \\ &= \sum_{0 \leq r < n_0} \sum_{q \in \mathbb{Z}} \mathbb{E} \left(e^{2i\pi m \sum_{l \in \mathbb{Z}} \mu_{\varepsilon_{l-q}} \lambda^{k+r+S_{l-q}}} \mathbf{1}_{S_{-u} < -r, u \geq 1, S_{-q} = -n-r} \right) \\ &= \sum_{0 \leq r < n_0} \sum_{q \in \mathbb{Z}} \mathbb{E} \left(e^{2i\pi m \sum_{l \in \mathbb{Z}} \mu_{\varepsilon_l} \lambda^{k+r+S_l}} \mathbf{1}_{S_{-u} < -r, u \geq 1, S_{-q} = -n-r} \right). \end{aligned}$$

For each $0 \leq r < n_0$, we can move the sum $\sum_{q \in \mathbb{Z}}$ inside the expectation, using the theorem of Fubini, if we for example show the finiteness of :

$$\sum_{q \in \mathbb{Z}} \mathbb{E} (1_{S_{-q} = -n-r}) = \mathbb{E} \left(\sum_{q \geq 0} 1_{S_{-q} = -n-r} \right) + \mathbb{E} \left(\sum_{q \geq 1} 1_{S_q = -n-r} \right).$$

This is true, since, as soon as n is larger than some constant (because of the missing term for $q = 0$ in the second sum), this equals $G^-(0, -n-r) + G^+(0, -n-r) < +\infty$, where $G^-(x, y)$ and $G^+(x, y)$ are the Green functions, finite for every integers x and y , respectively associated to the *i.i.d.* transient random walks $(S_{-q})_{q \geq 0}$ and $(S_q)_{q \geq 0}$. Let σ_k^+ , for $k \in \mathbb{Z}$, be the first time ≥ 0 when $(S_q)_{q \geq 0}$ touches k . Then $G^+(x, y) = \mathbb{P}_0(\sigma_{y-x}^+ < \infty)G^+(0, 0)$. With some symmetric quantities, we have $G^-(x, y) = \mathbb{P}_0(\sigma_{y-x}^- < \infty)G^-(0, 0)$.

We therefore obtain :

$$\mathbb{E} \left(e^{2i\pi m \sum_{l \in \mathbb{Z}} \mu_{\varepsilon_l} \lambda^{k-n+S_l}} \right) = \sum_{0 \leq r < n_0} \mathbb{E} \left(e^{2i\pi m \sum_{l \in \mathbb{Z}} \mu_{\varepsilon_l} \lambda^{k+r+S_l}} 1_{S_{-u} < -r, u \geq 1} \left(\sum_{q \in \mathbb{Z}} 1_{S_{-q} = -n-r} \right) \right).$$

Let us now fix $0 \leq r < n_0$ and consider the corresponding term. First of all, for $n > 0$ larger than some constant :

$$\mathbb{E} \left(\sum_{q < 0} 1_{S_{-q} = -n-r} \right) = \mathbb{P}_0(\sigma_{-n-r}^+ < \infty)G^+(0, 0) \rightarrow 0, \quad (8)$$

as $n \rightarrow +\infty$, since $(S_q)_{q \geq 0}$ is transient to the right. We thus only need to consider :

$$T(-n) := \mathbb{E} \left(e^{2i\pi m \sum_{l \in \mathbb{Z}} \mu_{\varepsilon_l} \lambda^{k+r+S_l}} 1_{S_{-u} < -r, u \geq 1} N(-n-r) \right),$$

where we set $N(-k-r) = \sum_{q \geq 0} 1_{S_{-q} = -n-r}$. Consider an integer M_0 , that we will let tend to $+\infty$ at the end. The difference of $T(-n)$ with the following expression :

$$\mathbb{E} \left(e^{2i\pi m \sum_{l \geq -M_0} \mu_{\varepsilon_l} \lambda^{k+r+S_l}} 1_{S_{-u} < -r, 1 \leq u \leq M_0} N(-n-r) \right)$$

is bounded by $A + B$, where, first :

$$\begin{aligned} A &= \mathbb{E} \left[\left| e^{2i\pi m \sum_{l \in \mathbb{Z}} \mu_{\varepsilon_l} \lambda^{k+r+S_l}} - e^{2i\pi m \sum_{l \geq -M_0} \mu_{\varepsilon_l} \lambda^{k+r+S_l}} \right| N(-n-r) \right] \\ &= \mathbb{E} \left[\left| 1 - e^{2i\pi m \sum_{l < -M_0} \mu_{\varepsilon_l} \lambda^{k+r+S_l}} \right| N(-n-r) \right] \\ &\leq \mathbb{E} \left(\left[\left| 1 - e^{2i\pi m \sum_{l < -M_0} \mu_{\varepsilon_l} \lambda^{k+r+S_l}} \right|^2 \right]^{1/2} (\mathbb{E}(N(-n-r)^2))^{1/2} \right) \\ &\leq \mathbb{E} \left(\left[\left| 1 - e^{2i\pi m \sum_{l < -M_0} \mu_{\varepsilon_l} \lambda^{k+r+S_l}} \right|^2 \right]^{1/2} (\mathbb{E}(N(0)^2))^{1/2} \right), \end{aligned}$$

because $N(-n-r)$ is stochastically dominated by $N(0)$. Notice that $N(0)$ is square integrable, as it has exponential tail. The first term on the right-hand side also goes to 0, as $M_0 \rightarrow +\infty$, by dominated convergence. The other term B is :

$$\begin{aligned}
B &= \mathbb{E} \left(\mathbf{1}_{S_{-u} < -r, 1 \leq u \leq M_0, \exists v > M_0, S_{-v} \geq -r} N(-n-r) \right) \\
&\leq \mathbb{P}(\exists v > M_0, S_{-v} \geq -r)^{1/2} \left(\mathbb{E}(N(-n-r)^2) \right)^{1/2} \\
&\leq \mathbb{P}(\exists v > M_0, S_{-v} \geq -r)^{1/2} \left(\mathbb{E}(N(0)^2) \right)^{1/2},
\end{aligned}$$

as before. The first term goes to 0, as $M_0 \rightarrow +\infty$, since (S_{-v}) is transient to $-\infty$, as $v \rightarrow +\infty$. As a result :

$$T(-n) = \mathbb{E} \left(e^{2i\pi m \sum_{l \geq -M_0} \mu_{\varepsilon_l} \lambda^{k+r+S_l}} \mathbf{1}_{S_{-u} < -r, 1 \leq u \leq M_0} N(-n-r) \right) + o_{M_0}(1),$$

where $o_{M_0}(1)$ goes to 0, as $M_0 \rightarrow +\infty$, uniformly in n . Now, when $n > 0$ is large enough, $N(-k-r) = \sum_{q \geq 0} \mathbf{1}_{S_{-q} = -n-r} = \sum_{q \geq M_0} \mathbf{1}_{S_{-q} = -n-r}$, for all ω . Taking inside the conditional expectation with respect to the σ -algebra generated by the $(\varepsilon_l)_{l \geq -M_0}$, we obtain :

$$T(-n) = \mathbb{E} \left(e^{2i\pi m \sum_{l \geq -M_0} \mu_{\varepsilon_l} \lambda^{k+r+S_l}} \mathbf{1}_{S_{-u} < -r, 1 \leq u \leq M_0} G^-(S_{-M_0}, -n-r) \right) + o_{M_0}(1).$$

Next, $G^-(S_{-M_0}, -n-r)$ is bounded by the constant $G^-(0,0)$. Hence, for some new $o_{M_0}(1)$, with the same properties :

$$T(-n) = \mathbb{E} \left(e^{2i\pi m \sum_{l \in \mathbb{Z}} \mu_{\varepsilon_l} \lambda^{k+r+S_l}} \mathbf{1}_{S_{-u} < -r, u \geq 1} G^-(S_{-M_0}, -n-r) \right) + o_{M_0}(1).$$

Since $G^-(S_{-M_0}, -n-r) \rightarrow 1/\mathbb{E}(n_{\varepsilon_0})$, by renewal theory (cf Woodroffe [21], chap. 2, thm 2.1), staying bounded by $G^-(0,0)$, we get by dominated convergence and next $M_0 \rightarrow +\infty$:

$$\lim_{n \rightarrow +\infty} T(-n) = \frac{1}{\mathbb{E}(n_{\varepsilon_0})} \mathbb{E} \left(e^{2i\pi m \sum_{l \in \mathbb{Z}} \mu_{\varepsilon_l} \lambda^{k+r+S_l}} \mathbf{1}_{S_{-u} < -r, u \geq 1} \right).$$

From the initial expression, the limit, if existing, had to be independent on k . So this proves the announced convergence and invariance.

Step 2. Assume now condition (C), hence that $n_0 \geq \dots \geq n_N \geq 1$. The φ_k are thus all strict contractions. Taking an integer $n \neq 0$, whose value will be fixed at the end, we consider the Fourier coefficient $\hat{m}(n)$ of the measure m appearing in the theorem. Removing the normalizing constant and observing that it has a simplified expression under condition (C), we introduce the following quantity, which is a constant multiple of it :

$$\Delta_p = \sum_{0 \leq r < n_0} \mathbb{E} \left(e^{2i\pi n \sum_{l \in \mathbb{Z}} \mu_{\varepsilon_l} \lambda^{r+S_l}} \mathbf{1}_{n_{\varepsilon_{-1}} > r} \right),$$

where we mark the dependence in $p \in \mathcal{C}_N$. We now focus on the regularity of $p \mapsto \Delta_p$ on \mathcal{C}_N . We shall prove using standard methods that it is continuous and in fact real-analytic on \mathcal{C}_N , in a sense precised below. Continuity of $p \mapsto \Delta_p$ is immediate, as this function is the uniform limit on \mathcal{C}_N , as $L \rightarrow +\infty$, of the continuous maps :

$$p \mapsto \sum_{0 \leq r < n_0} \mathbb{E} \left(e^{2i\pi n \sum_{-L \leq l \leq L} \mu_{\varepsilon_l} \lambda^{r+S_l}} \mathbf{1}_{n_{\varepsilon_{-1}} > r} \right).$$

For the real-analytic character, let us fix $0 \leq r < n_0$. Using independence, write :

$$\mathbb{E} \left(e^{2i\pi n \sum_{l \in \mathbb{Z}} \mu_{\varepsilon_l} \lambda^{r+S_l}} \mathbf{1}_{n_{\varepsilon_{-1}} > r} \right) = \mathbb{E} \left(e^{2i\pi n \sum_{l \geq 0} \mu_{\varepsilon_l} \lambda^{r+S_l}} \right) \mathbb{E} \left(e^{2i\pi n \sum_{l \leq -1} \mu_{\varepsilon_l} \lambda^{r+S_l}} \mathbf{1}_{n_{\varepsilon_{-1}} > r} \right).$$

Let us call $F(p)$ and $G(p)$ respectively the terms appearing in the right-hand side. We shall show that both functions are real-analytic functions (in the below sense) of p . This property will be

inherited by $p \mapsto \Delta_p$. We treat the case of $p \mapsto F(p)$, the case of $G(p)$ needing to rewrite first the $\mu_{\varepsilon_l} \lambda^{r+S_l}$, appearing in the definition of $G(p)$ and as soon as $l < 0$ is large enough (depending only the $(\mu_j)_{0 \leq j \leq N}$, since $n_k \geq 1$, for all k), as $-\sum_{1 \leq j \leq s} \alpha_j^{-r-S_l} \mu_{\varepsilon_l}^{(j)}$, quantity equal to $\mu_{\varepsilon_l} \lambda^{r+S_l}$ in \mathbb{T} , where the $(\mu_k^{(j)})_{1 \leq j \leq s}$ are the conjugates of μ_k in the field $\mathbb{Q}[1/\lambda]$.

Fix now $p \in \mathcal{C}_N$. Let $\mathbb{N} = \{0, 1, \dots\}$ and the symbolic space $S = \{0, \dots, N\}^{\mathbb{N}}$, equipped with the left shift σ . For $x = (x_0, x_1, \dots) \in S$, we define :

$$g(x) = e^{2i\pi n \left(\sum_{l \geq 0} \mu_{x_l} \lambda^{r+n x_0 + \dots + n x_{l-1}} \right)}.$$

Introducing the product measure $\mu_p = \left(\sum_{0 \leq j \leq N} p_j \delta_j \right)^{\otimes \mathbb{N}}$ on S , we can write :

$$F(p) = \int_S g \, d\mu_p.$$

Denote by $C(S)$ the space of continuous functions $f : S \rightarrow \mathbb{C}$ and introduce the operator $P_p : C(S) \rightarrow C(S)$ defined by :

$$P_p(f)(x) = \sum_{0 \leq j \leq N} p_j f((j, x)), \quad x \in S,$$

where $(j, x) \in S$ is the word obtained by the left concatenation of the symbol j to x . The operator P_p is Markovian, i.e. $f \geq 0 \Rightarrow P_p(f) \geq 0$ and verifies $P_p \mathbf{1} = \mathbf{1}$, where $\mathbf{1}(x) = 1$, $x \in S$. The measure μ_p has the invariance property $\int_S P_p(f) \, d\mu_p = \int_S f \, d\mu_p$, $f \in C(S)$. For $f \in C(S)$ and $k \geq 0$, introduce the variation :

$$\text{Var}_k(f) = \sup\{|f(x) - f(y)|, x_i = y_i, 0 \leq i < k\}.$$

For any $0 < \theta < 1$, let $|f|_\theta = \sup\{\theta^{-k} \text{Var}_k(f), k \geq 0\}$, as well as $\|f\|_\theta = |f|_\theta + \|f\|_\infty$. We denote by \mathcal{F}_θ the complex Banach space of functions f on S such that $\|f\|_\theta < \infty$. Any \mathcal{F}_θ is preserved by P_p . Observe now that $g \in \mathcal{F}_\theta$ for $\lambda \leq \theta < 1$. We take for example $\theta = \lambda$ and write \mathcal{F} for \mathcal{F}_θ .

As a classical fact from Spectral Theory, cf Ruelle [13] or Baladi [1], the operator $P_p : \mathcal{F} \rightarrow \mathcal{F}$ satisfies a Perron-Frobenius theorem : the eigenvalue 1 is simple and the rest of its spectrum is contained in a closed disk of radius $\rho < 1$. By standard functional holomorphic calculus, cf Kato [7], when taking for Γ the circle centered at 1 with radius $0 < r < 1 - \rho$, the following operator, involving the resolvent, is a continuous (Riesz) projector on $\text{Vect}(\mathbf{1})$:

$$\Pi_p = \int_\Gamma (zI - P_p)^{-1} dz.$$

Moreover, $\Pi_p(\mathcal{F})$ and $(I - \Pi_p)(\mathcal{F})$ are closed P_p -invariant subspaces with $\mathcal{F} = \Pi_p(\mathcal{F}) \oplus (I - \Pi_p)(\mathcal{F})$. In restriction to $(I - \Pi_p)(\mathcal{F})$, the spectral radius of P_p is less than ρ . In particular $\int_S f \, d\mu_p = 0$, for $f \in (I - \Pi_p)(\mathcal{F})$. This implies that for any $f \in \mathcal{F}$:

$$\Pi_p(f) = \left(\int_S f \, d\mu_p \right) \mathbf{1}.$$

Applying this to the function g of interest to us, we obtain that :

$$F(p)\mathbf{1} = \int_\Gamma (zI - P_p)^{-1}(g) dz.$$

Recall now that $N \geq 1$. Let $\eta' = (\eta_0, \dots, \eta_{N-1})$ and $\eta = (\eta_0, \dots, \eta_{N-1}, -(\eta_0 + \dots + \eta_{N-1}))$. The condition on η' for $p + \eta \in \mathcal{C}_N$ is written as $\eta' \in D_N(p)$. Explicitly the condition is :

$$-p_i \leq \eta_i \leq 1 - p_i, \quad 0 \leq i \leq N - 1, \quad \text{and} \quad p_N - 1 \leq \eta_0 + \dots + \eta_{N-1} \leq p_N.$$

For the sequel, let $B_N(0, R)$ be the open Euclidean ball in \mathbb{R}^N centered at 0, of radius R .

Definition 4.1

A function $h : \mathcal{C}_N \rightarrow \mathbb{C}$ admits a development in series around a point $p \in \mathcal{C}_N$, if there exists $\varepsilon > 0$ such that for $\eta' = (\eta_0, \dots, \eta_{N-1}) \in D_N(p) \cap B_N(0, \varepsilon)$ and writing $\eta = (\eta_0, \dots, \eta_{N-1}, -(\eta_0 + \dots + \eta_{N-1}))$, then $h(p + \eta)$ is given by an absolutely converging series :

$$h(p + \eta) = \sum_{l_0 \geq 0, \dots, l_{N-1} \geq 0} A_{l_0, \dots, l_{N-1}} \eta_0^{l_0} \cdots \eta_{N-1}^{l_{N-1}}.$$

A function is real-analytic in \mathcal{C}_N if it admits a development in series around every $p \in \mathcal{C}_N$.

For such a function, when non-constant, its zeroes are in finite number in \mathcal{C}_N , by the standard argument that the set of points where there is a null development in series is open and closed for the relative topology and thus equal to \mathcal{C}_N by connexity if non-empty. In case of infinitely many zeros, any accumulation point (which exists, as \mathcal{C}_N is compact) is such a point.

We now check below that $p \mapsto F(p)$ is real-analytic in the previous sense. As already indicated, this property will be inherited by $p \mapsto \Delta_p$. In this direction, notice that :

$$P_{p+\eta} = P_p + \sum_{0 \leq j \leq N-1} \eta_j Q_j,$$

where $Q_j(f)(x) = f(j, x) - f(N, x)$. For $z \in \Gamma$ and η' small enough :

$$\begin{aligned} (zI - P_{p+\eta})^{-1} &= \left(I - (zI - P_p)^{-1} \sum_{0 \leq j \leq N-1} \eta_j Q_j \right)^{-1} (zI - P_p)^{-1} \\ &= \sum_{n \geq 0} \sum_{0 \leq j_1, \dots, j_n \leq N-1} \eta_{j_1} \cdots \eta_{j_n} (zI - P_p)^{-1} Q_{j_1} \cdots (zI - P_p)^{-1} Q_{j_n} (zI - P_p)^{-1}. \end{aligned}$$

This is clearly absolutely convergent in the Banach operator algebra, for small enough η' , uniformly in $z \in \Gamma$. We rewrite it as :

$$(zI - P_{p+\eta})^{-1} = \sum_{l_0 \geq 0, \dots, l_{N-1} \geq 0} B_{l_0, \dots, l_{N-1}}(z) \eta_0^{l_0} \cdots \eta_{N-1}^{l_{N-1}},$$

converging for the operator norm, uniformly in $z \in \Gamma$. This leads to :

$$F(p + \eta)\mathbf{1} = \int_{\Gamma} (zI - P_{p+\eta})^{-1}(g) dz = \sum_{l_0 \geq 0, \dots, l_{N-1} \geq 0} \eta_0^{l_0} \cdots \eta_{N-1}^{l_{N-1}} \int_{\Gamma} B_{l_0, \dots, l_{N-1}}(z)(g) dz.$$

Applying this equality at some particular $x \in S$, we obtain the desired development in series around p . This completes this step.

Step 3. We finish the proof of point *iii*) of the theorem. If ever $\Delta_p = 0$ for infinitely many $p \in \mathcal{C}_N$, then by *Step 2*, $p \mapsto \Delta_p$ has to be constant and equal to zero on \mathcal{C}_N . We shall show that if $n \neq 0$ has been appropriately chosen at the beginning it is not possible. We start with a lemma. We write as $x \equiv y$ equality of x and y in \mathbb{T} .

Lemma 4.2

Let $d \geq 1$ and $\mu \in \mathcal{T}(1/\lambda)$. The series $\sum_{l \in \mathbb{Z}} \mu \lambda^{ld}$, well-defined as an element of \mathbb{T} , equals a rational number modulo 1.

Proof of the lemma :

Let $l_0 \geq 1$ be such that $Tr(\lambda^{-l_0} \mu) \in \mathbb{Z}$, for $l > l_0$. Denote by $(\mu^{(j)})_{0 \leq j \leq s}$ the conjugates of μ , with $\mu^{(0)} = \mu$, and $\alpha_1, \dots, \alpha_s$ that of $\alpha_0 = 1/\lambda$. Then, we have the following equalities on the torus :

$$\begin{aligned}
\sum_{l \in \mathbb{Z}} \mu \lambda^{ld} &\equiv \frac{\mu \lambda^{-l_0 d}}{1 - \lambda^d} + \sum_{l > l_0} \mu \lambda^{-ld} \equiv \frac{\mu \lambda^{-l_0 d}}{1 - \lambda^d} - \sum_{1 \leq i \leq s} \mu^{(i)} \sum_{l > l_0} \alpha_i^{ld} \equiv \frac{\mu \lambda^{-l_0 d}}{1 - \lambda^d} - \sum_{1 \leq i \leq s} \mu^{(i)} \frac{\alpha_i^{(l_0+1)d}}{1 - \alpha_i^d} \\
&\equiv - \left(\frac{\mu \lambda^{-(l_0+1)d}}{1 - \lambda^{-d}} + \sum_{1 \leq i \leq s} \mu^{(i)} \frac{\alpha_i^{(l_0+1)d}}{1 - \alpha_i^d} \right) = -Tr \left(\frac{\mu \lambda^{-(l_0+1)d}}{1 - \lambda^{-d}} \right) \in \mathbb{Q}.
\end{aligned}$$

□

We conclude the argument. Fixing $0 \leq j \leq N$ and $p^j = (0, \dots, 0, 1, 0, \dots, 0)$, where the 1 is at place j , we have for $k \in \mathbb{Z}$, recalling that $1 \leq n_j \leq n_0$:

$$\Delta_{p^j} = \sum_{0 \leq r < n_j} e^{2i\pi n \sum_{l \in \mathbb{Z}} \mu_j \lambda^{r+ln_j}} = \sum_{0 \leq r < n_j} e^{2i\pi n(A_{j,r}/B_{j,r})},$$

for rational numbers $A_{j,r}/B_{j,r}$, making use of the previous lemma, since $\lambda^r \mu \in \mathcal{T}(1/\lambda)$, for any r . In fact in this case, m is the purely atomic measure :

$$m = \frac{1}{n_j} \sum_{0 \leq r < n_j} \delta_{A_{j,r}/B_{j,r}}.$$

If for example n is a multiple of $B_{j,r}$ for any $0 \leq r < n_j$, we get $\Delta_{p^j} = n_j \geq 1$, which gives what was desired. This ends the proof of the theorem. □

Remark. — In the general case, without condition (C), the method seems to reach some limit. When trying to analyze the regularity of $p \mapsto F(p)$ on $\mathcal{D}_N((\lambda^{n_k})_{0 \leq k \leq N})$, continuity seems rather clear, but the real-analytic character, if ever true, certainly requires more work. Still with $S = \{0, \dots, N\}^{\mathbb{N}}$ and $\mu_p = (\sum_{0 \leq j \leq N} p_j \delta_j)^{\otimes \mathbb{N}}$ on S , we again have :

$$F(p) = \int_S g \, d\mu_p,$$

with $g(x) = e^{2i\pi n (\sum_{l \geq 0} \mu_{x_l} \lambda^{r+n_{x_0}+\dots+n_{x_{l-1}}})}$, for $x = (x_0, x_1, \dots) \in S$, but this function is not continuous on S and in fact only defined μ_p -almost-everywhere.

5 Complements

5.1 A numerical example

Considering an example as simple as possible which is not homogeneous, take $N = 1$ and the two contractions $\varphi_0(x) = \lambda x$, $\varphi_1(x) = 1 + \lambda^2 x$, where $1/\lambda > 1$ is a Pisot number, with probability vector $p = (p_0, p_1)$. Then $n_0 = 1$ and $n_1 = 2$ and ν is the law of $\sum_{l \geq 0} \varepsilon_l \lambda^{n_{\varepsilon_0} + \dots + n_{\varepsilon_{l-1}}}$, with $(\varepsilon_n)_{n \geq 0}$ *i.i.d.*, with common law $\text{Ber}(p_1)$. We shall take $0 \leq p_1 \leq 1$ as parameter for simulations. For example $\mathbb{E}(n_{\varepsilon_0}) = p_0 + 2p_1 = 1 + p_1$,

Taking $n = 1$, $k \in \mathbb{Z}$ and $r \in \{0, 1\}$, let us define :

$$F_p(k) = \mathbb{E} \left(e^{2i\pi \lambda^k \sum_{l \geq 0} \varepsilon_l \lambda^{n_{\varepsilon_0} + \dots + n_{\varepsilon_{l-1}}} } \right), \quad G_p(k, r) = \mathbb{E} \left(e^{2i\pi \sum_{l \geq 0} \varepsilon_l \lambda^{k - (n_{\varepsilon_0} + \dots + n_{\varepsilon_l})} } 1_{n_{\varepsilon_0} > r} \right),$$

leading to $\Delta_p = F_p(k)G_p(k, 0) + F_p(k+1)G_p(k+1, 1)$, for all $k \in \mathbb{Z}$. Writing m_p in place of m for the measure on \mathbb{T} in Theorem 2.4, we get $\hat{m}_p(1) = \Delta_p/(1 + p_1)$. Let us first discuss the choice of $p = (1 - p_1, p_1)$ and Pisot number $1/\lambda$.

A degenerated example (the invariant measure being automatically singular) is for instance given by $\lambda = (3 - \sqrt{5})/2 < 1/2$. Nevertheless, it is interesting to notice that $\lambda^{-n} \equiv -\lambda^n$, $n \geq 0$.

Taking $p_1 = 1/2$, one can check that $\Delta_p = |F_p(1)|^2 + |F_p(2)|^2/2$. Necessarily $\Delta_p > 0$. Indeed, $k \mapsto F_p(k)$ verifying a linear recurrence of order two with respect to k , the equality $\Delta_p = 0$ would give $F_p(k) = 0$ for all k , but $F_p(k) \rightarrow 1$, as $k \rightarrow +\infty$. Notice that $(3 - \sqrt{5})/2$ is the largest λ with this property (it has to be a root of some $X^2 - aX + 1$, for some integer $a \geq 0$). Mention that in general Δ_p is not real; cf the pictures below.

To study an interesting example, we take into account the similarity dimension $s(p, r)$, rewritten here as $s(p, \lambda)$:

$$s(p, \lambda) = \frac{(1 - p_1) \ln(1 - p_1) + p_1 \ln p_1}{(1 - p_1) \ln \lambda + p_1 \ln(\lambda^2)}.$$

The condition $s(p, \lambda) \geq 1$ is equivalent to $(1 - p_1) \ln(1 - p_1) + p_1 \ln p_1 - (1 + p_1) \ln \lambda \leq 0$. As a function of p_1 , the left-hand side has a minimum value $-\ln(\lambda + \lambda^2)$, attained at $p_1 = \lambda/(1 + \lambda)$. As a first attempt, taking for $1/\lambda$ the golden mean $(\sqrt{5} + 1)/2 = 1,618\dots$ appears in fact not to be a good idea, as in this case $\lambda + \lambda^2 = 1$, giving $s(p, \lambda) \leq 1$.

We instead take for $1/\lambda$ the Plastic number, the smallest Pisot number (cf Siegel [17]). It is defined as the unique real root of $X^3 - X - 1$. Approximately, $1/\lambda = 1.324718\dots$. For this λ :

$$s(p, \lambda) > 1 \iff 0,203\dots < p_0 < 0,907\dots$$

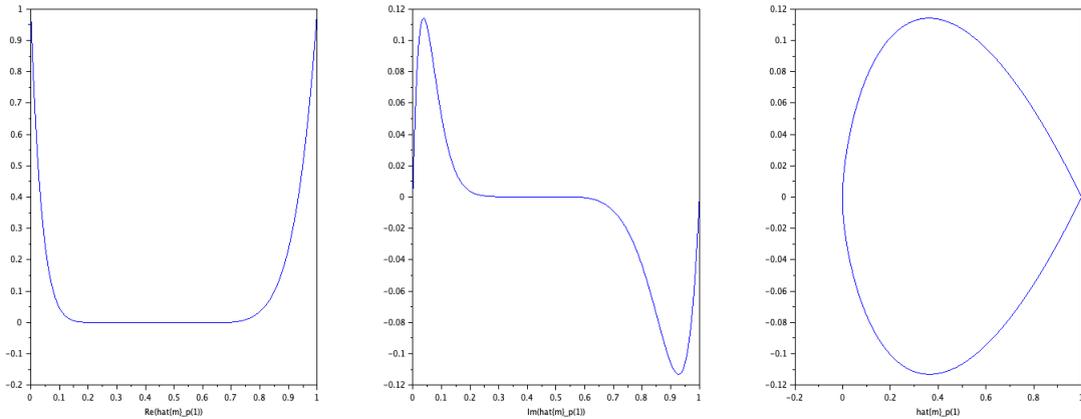
The other roots of $X^3 - X - 1 = 0$ are conjugate numbers $\rho e^{\pm i\theta}$. From the relations $1/\lambda + 2\rho \cos \theta = 0$ and $(1/\lambda)\rho^2 = 1$, we deduce $\rho = \sqrt{\lambda}$ and $\cos \theta = -1/(2\lambda^{3/2})$, thus $\theta = \pm 2.43\dots$ rad. For computations, the relations $\lambda^{-n} + \rho^n e^{in\theta} + \rho^n e^{-in\theta} \in \mathbb{Z}$, $n \geq 0$, furnish $\lambda^{-n} \equiv -2(\sqrt{\lambda})^n \cos(n\theta)$.

Let us finally compute the extreme values of $p_1 \mapsto \hat{m}_p(1)$. We first observe that $\hat{m}_{(1,0)}(1) = \Delta_{(1,0)} = F_{(1,0)}(0)G_{(1,0)}(0,0) = 1$. At the other extremity :

$$\begin{aligned} \Delta_{(0,1)} &= F_{(0,1)}(0)G_{(0,1)}(0,0) + F_{(0,1)}(1)G_{(0,1)}(1,1) \\ &= e^{2i\pi \sum_{l \geq 0} \lambda^{2l}} e^{2i\pi \sum_{l \geq 0} \lambda^{-2(l+1)}} + e^{2i\pi \lambda \sum_{l \geq 0} \lambda^{2l}} e^{2i\pi \sum_{l \geq 0} \lambda^{1-2(l+1)}} \\ &= e^{2i\pi \left(\frac{1}{1-\lambda^2} - 2 \sum_{l \geq 0} (\sqrt{\lambda})^{2l} \cos(2l\theta) \right)} + e^{2i\pi \left(\frac{\lambda}{1-\lambda^2} - 2 \sum_{l \geq 0} (\sqrt{\lambda})^{2l+1} \cos((2l+1)\theta) \right)} \\ &= e^{2i\pi \left(\frac{1}{1-\lambda^2} - 2 \operatorname{Re} \left(\frac{\lambda e^{2i\theta}}{1-\lambda e^{2i\theta}} \right) \right)} + e^{2i\pi \left(\frac{\lambda}{1-\lambda^2} - 2 \operatorname{Re} \left(\frac{\sqrt{\lambda} e^{i\theta}}{1-\lambda e^{2i\theta}} \right) \right)}. \end{aligned}$$

A not difficult computation, shortened by the observation that $(1 - \lambda e^{2i\theta})(1 - \lambda e^{-2i\theta}) = 1/\lambda$, shows that the arguments in the exponential terms (after the $2i\pi$) are respectively equal to 3 and 0, leading to $\Delta_{(0,1)} = 2$ and therefore $\hat{m}_{(0,1)}(1) = 1$.

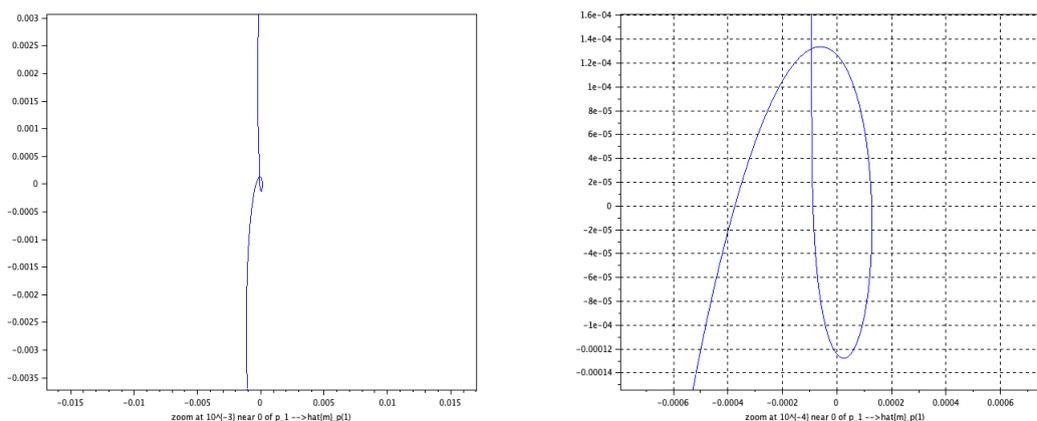
Recalling that $p = (1 - p_1, p_1)$, below are respectively drawn the real-analytic maps $p_1 \mapsto \operatorname{Re}(\hat{m}_p(1))$, $p_1 \mapsto \operatorname{Im}(\hat{m}_p(1))$ and the parametric curve $p_1 \mapsto \hat{m}_p(1)$, $0 \leq p_1 \leq 1$.



The first two pictures indicate that $p_1 \mapsto \hat{m}_p(1)$ spends a rather long time near 0, with $\text{Re}(\hat{m}_p(1))$ and $\text{Im}(\hat{m}_p(1))$ both around 10^{-4} . Let us precise here that one can exploit the product form (given by the exponential) inside the expectation appearing in $F_p(k)$ and $G_p(k, r)$ and make a deterministic numerical computation of $\hat{m}_p(1)$, with nearly an arbitrary precision, based on a dynamical programming (using a binomial tree). For example, one can obtain the rather remarkable value :

$$\hat{m}_{(1/2, 1/2)}(1) = 0,000118\dots + i0,0000327\dots,$$

where all digits are exact. In this case, $s((1/2, 1/2), \lambda) = 1,64\dots > 1$. The above pictures were drawn with 1000 points, each one determined with a sufficient precision. This allows to safely zoom on the neighbourhood of 0, the interesting region. We obtain the following surprising pictures, the one on the right-hand side containing around 500 points :



One might guess the existence of profound reasons behind these pictures, that would in particular clarify the condition of non-nullity of the Fourier coefficient $\hat{m}(1)$ and more generally of $\hat{m}(n)$, $n \in \mathbb{Z}$. Further investigations are necessary.

From the previous numerical analysis, we conclude that the curve $p_1 \mapsto \hat{m}_p(1)$ is rather convincingly not touching 0. It may certainly be possible to build a rigorous numerical proof of this fact, but this is not the purpose of the present paper. Being confident in this, we can state :

Numerical Theorem 5.1

Let $N = 1$ and the two contractions $\varphi_0(x) = \lambda x$ and $\varphi_1(x) = 1 + \lambda^2 x$, where $1/\lambda > 1$ is the Plastic number. Then for any probability vector $p \in \mathcal{C}_1$, the invariant measure ν is not Rajchman.

Remark. — A similar study developed with $1/\lambda$ the supergolden ratio, i.e. the fourth Pisot number (the real root of $X^3 - X^2 - 1$) leads to essentially the same pictures. Further numerical investigations with the family $\varphi_0(x) = \lambda x$, $\varphi_1(x) = \lambda^2 x$ and $\varphi_2(x) = \lambda^2 x + 1$, for $1/\lambda$ the Plastic number, reveal rather clearly the existence of parameters $p \in \mathcal{C}_2$ for which $\hat{m}(1) = 0$.

5.2 Applications to sets of uniqueness for trigonometric series

Let $N \geq 1$ and for $0 \leq k \leq N$ affine contractions $\varphi_k(x) = r_k x + b_k$, with reals (r_k) and (b_k) , with $0 < r_k < 1$ for all k (i.e. condition (C) holds). As a general fact, Theorem 2.3 has some consequences in terms of sets of multiplicity for trigonometric series, cf for example Salem [15] or Zygmund [22] for details. As in the introduction, let $F \subset \mathbb{R}$ be the unique non-empty compact set, verifying the self-similarity relation $F = \cup_{0 \leq k \leq N} \varphi_k(F)$.

Let us place on the torus \mathbb{T} and consider trigonometric series. Recall that a subset E of the torus is a set of uniqueness (U -set), if whenever a trigonometric series $\sum_{n \geq 0} (a_n \cos(2\pi x) + b_n \sin(2\pi x))$, with complex numbers (a_n) and (b_n) , converges to 0 for $x \notin E$, then $a_n = b_n = 0$ for all $n \geq 0$. Otherwise E is said of multiplicity (M -set).

Theorem 5.1

Let $N \geq 1$ and for $0 \leq k \leq N$ affine contractions $\varphi_k(x) = r_k x + b_k$, where $0 < r_k < 1$, with no common fixed point. Suppose that the system $(\varphi_k)_{0 \leq k \leq N}$ is not conjugated to a family in reduced Pisot form. Then $F \bmod 1 \subset \mathbb{T}$ is a M -set.

Proof of the theorem :

Taking any $p \in \mathcal{C}_N$ with $p_j > 0$, for all $0 \leq j \leq N$, gives a Rajchman invariant probability measure ν supported by $F \subset \mathbb{R}$. Hence $F \bmod 1 \subset \mathbb{T}$ supports the probability measure $\tilde{\nu}$, image of ν under the projection $x \mapsto x \bmod 1$, from \mathbb{R} to \mathbb{T} . The measure $\tilde{\nu}$ is thus a Rajchman measure on \mathbb{T} , so, cf Salem [15] (chap. V), $F \bmod 1$ is a M -set. □

The analysis in the other direction is in general more delicate. We introduce as before the symbolic space $S = \{0, \dots, N\}^{\mathbb{N}}$, with $\mathbb{N} = \{0, 1, \dots\}$.

Theorem 5.2

Let $N \geq 1$ and suppose that the (φ_k) are affine contractions of the form $\varphi_k(x) = \lambda^{n_k} x + b_k$, with $b_k = ba_k + c(1 - \lambda^{n_k})$, for some $0 < \lambda < 1$ with $1/\lambda$ a Pisot number $> N + 2$, relatively prime positive integers $n_k \geq 1$, $0 \leq a_k \in \mathbb{Q}[\lambda]$ and real numbers $b \geq 0$ and c . Then the non-empty compact self-similar set $F = \cup_{0 \leq k \leq N} \varphi_k(F) \subset \mathbb{R}$ can be written as $F = bG + c$, where G is the compact set :

$$G = \left\{ \sum_{l \geq 0} a_{x_l} \lambda^{n_{x_0} + \dots + n_{x_{l-1}}}, (x_0, x_1, \dots) \in S \right\}.$$

Assume that $bG \subset [0, 1)$, so that bG and F can be seen as subsets of \mathbb{T} . Then F is U -set.

Proof of the theorem :

Up to replacing b and the (a_k) respectively by br and (a_k/r) , for some $r > 1$ in \mathbb{Q} , we may assume that $0 \leq a_k < 1/(1 - \lambda)$, for all $0 \leq k \leq N$. Then :

$$G \subset H := \left\{ \sum_{l \geq 0} \eta_l \lambda^l, \eta_l \in \{0, a_0, \dots, a_N\}, l \geq 0 \right\} \subset [0, 1).$$

Since $1/\lambda > N + 2$ is a Pisot number and all a_0, \dots, a_N are in $\mathbb{Q}[\lambda]$, it follows from the Salem-Zygmund theorem, cf Salem [15], chap. VII, paragraph 3, on perfect homogeneous sets, that H is a perfect U -set. Mention that in this theorem, one also assumes that $\max_{0 \leq k \leq N} a_k = 1/(1 - \lambda)$ and that successive $a_u < a_v$ in $[0, 1)$ verify $a_v - a_u \geq \lambda$. These conditions serve to give a geometrical description of the perfect homogeneous set H in terms of dissection, without overlaps. They are in fact not used in the proof, where only the above description of H is important (one can indeed start reading Salem [15], chap. VII, paragraph 3, directly from line 9 of the proof).

As a subset of a U -set, G is also a U -set. This is also the case of bG , by hypothesis a subset of $[0, 1)$, using Zygmund, Vol. I, chap. IX, Theorem 6.18 (the proof, not obvious, is in Vol. II, chap. XVI, 10.25, and relies on Fourier integrals). Hence, $F = bG + c$ is also a U -set, as any translate on \mathbb{T} of a U -set is a U -set. This ends the proof of the theorem. □

Remark. — As a general fact, the hypothesis $1/\lambda > N + 2$ ensures that H and thus F have zero Lebesgue measure, which is a necessary condition for a set to be a U -set. If overlaps happen in H , it would be interesting to consider extensions of the previous theorem, when the above condition on λ not necessarily holds.

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