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DIRICHLET UNIFORMLY WELL-APPROXIMATED NUMBERS

DONG HAN KIM AND LINGMIN LIAO

ABSTRACT. Denote by $\|\cdot\|$ the distance of a real number to its nearest integer. Fix an irrational θ . For a real number $\tau > 0$, consider the numbers y satisfying that for all large number $Q \gg 1$, there exists an integer $1 \leq n \leq Q$, such that $\|n\theta - y\| < Q^{-\tau}$. These numbers are called Dirichlet uniformly well-approximated numbers. For any $\tau > 0$, the Hausdorff dimension of the set of these numbers is obtained and is shown to depend on the irrationality exponent $w(\theta) := \sup\{s > 0 : \liminf_{j \rightarrow \infty} j^s \|j\theta\| = 0\}$ of θ . It is also proved that with respect to τ , the only possible discontinuous point of the Hausdorff dimension is $\tau = 1$.

1. INTRODUCTION

In Diophantine approximation, we study the approximation of an irrational number by rationals. Denote by $\|t\| = \min_{n \in \mathbb{Z}} |t - n|$ the distance from a real t to the nearest integer. In 1842, Dirichlet [10] showed the his celebrated theorem of Diophantine approximation:

Dirichlet Theorem *Let θ, Q be real numbers with $Q \geq 1$. There exists an integer n with $1 \leq n \leq Q$, such that $\|n\theta\| < Q^{-1}$.*

Following Waldschmidt [40], we call the Dirichlet Theorem a *uniform approximation theorem*. A weak form of the theorem, called an *asymptotic approximation theorem*, is already known (e.g., Legendre's 1808 book [30, pp.18–19])¹ before Dirichlet: for any real θ , there exist infinitely many integers n such that $\|n\theta\| < n^{-1}$. In the literature, much more attention is paid to the asymptotic approximation.

The first inhomogeneous asymptotic approximation result is due to Minkowski [33] in 1907. Let θ be an irrational. Let y be a real number which is not equal to any $m\theta + \ell$ with $m, \ell \in \mathbb{N}$. Minkowski proved that there exist infinitely many integers n such that $\|n\theta - y\| < \frac{1}{4|n|}$.

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In 1924, Khinchine [22] proved that for a continuous function $\Psi : \mathbb{N} \rightarrow \mathbb{R}^+$, if $x \mapsto x\Psi(x)$ is non-increasing, then the set

$$\mathcal{L}_\Psi := \{\theta \in \mathbb{R} : \|n\theta\| < \Psi(n) \text{ for infinitely many } n\}$$

has Lebesgue measure zero if the series $\sum \Psi(n)$ converges and has full Lebesgue measure otherwise. The expected similar result by deleting the non-increasing condition on Ψ is the famous Duffin-Schaeffer conjecture [11]. One could find the recent developments in Haynes–Pollington–Velani–Sanju [17] and Beresnevich–Harman–Haynes–Velani [3].

For the inhomogeneous cases, Khinchine’s theorem was extended to the set

$$\mathcal{L}_\Psi(y) := \{\theta \in \mathbb{R} : \|n\theta - y\| < \Psi(n) \text{ for infinitely many } n\}$$

by Szűsz [39] and Schmidt [36]. On the other hand, it follows from the Borel-Cantelli Lemma that the Lebesgue measure of

$$\mathcal{L}_\Psi[\theta] := \{y \in \mathbb{R} : \|n\theta - y\| < \Psi(n) \text{ for infinitely many } n\}$$

is zero whenever the series $\sum \Psi(n)$ converges. However, it seems not easy to obtain a full Lebesgue measure result. In 1955, Kurzweil [28] showed that, if the irrational θ is of bounded type, then for a monotone decreasing function $\Psi : \mathbb{N} \rightarrow \mathbb{R}^+$, with $\sum \Psi(n) = \infty$, the set $\mathcal{L}_\Psi[\theta]$ has full Lebesgue measure. In 1957, Cassels [6] proved that for almost all θ , the set $\mathcal{L}_\Psi[\theta]$ has full Lebesgue measure if $\sum \Psi(n) = \infty$. For new results in this direction, we refer to the recent works Laurent–Nogueira [29], Kim [26], and Fuchs–Kim [15].

At the end of twenties of last century, the concept of Hausdorff dimension had been introduced into the study of Diophantine approximation. We refer the reader to [12] for the definition and properties of the Hausdorff dimension. Using the notion of Hausdorff dimension, Jarník ([16], 1929) and independently Besicovitch ([2], 1934) studied the size of the set of asymptotically well-approximated numbers. They proved that for any $\tau \geq 1$, the Hausdorff dimension of the set

$$\mathcal{L}_\tau(0) := \{\theta \in \mathbb{R} : \|n\theta\| < n^{-\tau} \text{ for infinitely many } n\}$$

is $2/(\tau + 1)$.

The corresponding inhomogeneous question was solved by Levesley [31] in 1998: for any $\tau \geq 1$, and any real number y , the Hausdorff dimension of the set

$$\mathcal{L}_\tau(y) := \{\theta \in \mathbb{R} : \|n\theta - y\| < n^{-\tau} \text{ for infinitely many } n\}$$

which is different from $\mathcal{L}_\tau(0)$, is also $2/(\tau + 1)$.

As in the Lebesgue measure problems, for the inhomogeneous case, one is also concerned with the Hausdorff dimension of the sets of inhomogeneous terms. For a fixed irrational θ , let us denote

$$\mathcal{L}_\tau[\theta] := \{y \in \mathbb{R} : \|n\theta - y\| < n^{-\tau} \text{ for infinitely many } n\}.$$

In 2003, Bugeaud [4] and independently, Schmeling and Troubetzkoy [35] showed that for $\tau \geq 1$ the Hausdorff dimension of the set $\mathcal{L}_\tau[\theta]$ is $1/\tau$.

In analogy to the asymptotic approximation, for $\tau > 0$, we consider the following uniform approximation sets:

$$\begin{aligned} \mathcal{U}_\tau(y) &:= \{\theta \in \mathbb{R} : \text{for all large } Q, 1 \leq \exists n \leq Q \text{ such that } \|n\theta - y\| < Q^{-\tau}\}, \\ \mathcal{U}_\tau[\theta] &:= \{y \in \mathbb{R} : \text{for all large } Q, 1 \leq \exists n \leq Q \text{ such that } \|n\theta - y\| < Q^{-\tau}\}. \end{aligned}$$

The points in $\mathcal{U}_\tau(y)$ and $\mathcal{U}_\tau[\theta]$ are called Dirichlet uniformly well-approximated numbers. The set $\mathcal{U}_\tau(0)$ is referred to as homogeneous uniform approximation. We see from Dirichlet Theorem that $\mathcal{U}_1(0) = \mathbb{R}$. However, Khintchine [23] showed that for all $\tau > 1$, $\mathcal{U}_\tau(0)$ is \mathbb{Q} . In general, for $y \in \mathbb{R}$, the set $\mathcal{U}_1(y)$ does not always contain all irrationals. Thus, there is no inhomogeneous analogy of the Dirichlet Theorem. For higher dimensional analogy of $\mathcal{U}_\tau(0)$, Cheung [7] proved that the set of points (θ_1, θ_2) such that for any $\delta > 0$, for all large Q , there exists $n \leq Q$ such that

$$\max\{\|n\theta_1\|, \|n\theta_2\|\} < \delta/Q^{\frac{1}{2}},$$

is of Hausdorff dimension $4/3$. This result was recently generalized to dimension larger than 3 by Cheung and Chevallier [8].

In this paper, we mainly study the set $\mathcal{U}_\tau[\theta]$. We will restrict ourselves on the unit circle $\mathbb{T} = \mathbb{R}/\mathbb{Z}$, for which the dimension results will be the same to those on \mathbb{R} . The points in \mathbb{T} are considered as the same as their fractional parts. Denote by \dim_H the Hausdorff dimension. Let $q_n = q_n(\theta)$ be the denominator of the n -th convergent of the continued fraction of θ . The following main theorems show that $\dim_H(\mathcal{U}_\tau[\theta])$ can be obtained using the sequence $q_n(\theta)$ and strongly depends on the irrationality exponent of θ :

$$w(\theta) := \sup\{s > 0 : \liminf_{j \rightarrow \infty} j^s \|j\theta\| = 0\}.$$

Theorem 1. *Let θ be an irrational with $w(\theta) > 1$. Then $\mathcal{U}_\tau[\theta] = \mathbb{T}$ if $\tau < 1/w(\theta)$; $\mathcal{U}_\tau[\theta] = \{i\theta \in \mathbb{T} : i \geq 1\}$ if $\tau > w(\theta)$; and*

$$\dim_H(\mathcal{U}_\tau[\theta]) = \begin{cases} \liminf_{k \rightarrow \infty} \frac{\log\left(n_k^{1/\tau+1} \prod_{j=1}^{k-1} n_j^{1/\tau} \|n_j\theta\|\right)}{\log(n_k \|n_k\theta\|^{-1})}, & \frac{1}{w(\theta)} < \tau < 1, \\ \liminf_{k \rightarrow \infty} \frac{-\log\left(\prod_{j=1}^{k-1} n_j \|n_j\theta\|^{1/\tau}\right)}{\log(n_k \|n_k\theta\|^{-1})}, & 1 < \tau < w(\theta). \end{cases}$$

where n_k is the (maximal) subsequence of (q_k) such that

$$\begin{cases} n_k \|n_k\theta\|^\tau < 1, & \text{if } 1/w(\theta) < \tau < 1, \\ n_k^\tau \|n_k\theta\| < 2, & \text{if } 1 < \tau < w(\theta). \end{cases}$$

Theorem 2. *For any irrational θ with $w(\theta) = 1$, we have $\mathcal{U}_\tau[\theta] = \mathbb{T}$ if $\tau < 1$; $\mathcal{U}_\tau[\theta] = \{i\theta : i \geq 1\}$ if $\tau > 1$; and*

$$\frac{1}{2} \leq \dim_H(\mathcal{U}_\tau[\theta]) \leq 1, \quad \text{if } \tau = 1.$$

By Theorem 1, we have the following bounds of dimension in terms of $w(\theta)$.

Theorem 3. *For any irrational θ with $w(\theta) = w > 1$, we have*

$$\begin{aligned} \frac{w/\tau - 1}{w^2 - 1} \leq \dim_H(\mathcal{U}_\tau[\theta]) &\leq \frac{1/\tau + 1}{w + 1}, & \frac{1}{w} \leq \tau \leq 1, \\ 0 \leq \dim_H(\mathcal{U}_\tau[\theta]) &\leq \frac{w/\tau - 1}{w^2 - 1}, & 1 < \tau \leq w. \end{aligned}$$

Moreover, if $w(\theta) = \infty$, then $\dim_H(\mathcal{U}_\tau[\theta]) = 0$ for all $\tau > 0$.

We will show in Examples 17, 18, 19 and 20, that the upper and lower bounds of Theorems 2 and 3 can be all reached.

Remark 4. Consider the case $\tau > 1$. By optimizing the upper bound in Theorem 3 with respect to w , we have for $\tau > 1$,

$$\dim_H(\mathcal{U}_\tau[\theta]) \leq \frac{1}{2\tau(\tau + \sqrt{\tau^2 - 1})},$$

and the equality holds when $w = \tau + \sqrt{\tau^2 - 1}$. Since $\tau + \sqrt{\tau^2 - 1} > \tau$, we deduce that

$$\dim_H(\mathcal{U}_\tau[\theta]) < \frac{1}{2\tau^2} < \frac{1}{2\tau} \quad \text{for all } \tau > 1.$$

We know that for all $\tau > 1$, $\mathcal{U}_\tau[\theta]$ is included in $\mathcal{L}_\tau[\theta]$ except for a countable set of points. Recall that $\dim_H(\mathcal{L}_\tau[\theta]) = 1/\tau$ for all $\tau > 1$. Our result then shows that the inclusion is strict in the sense of Hausdorff dimension. In fact, the former is strictly less than one-half of the later one by Hausdorff dimension.

In this paper, we will also prove the following theorem on the continuity of the Hausdorff dimension of the set $\mathcal{U}_\tau[\theta]$ with respect to the parameter θ .

Theorem 5. *For each irrational θ , $\dim_H(\mathcal{U}_\tau[\theta])$ is a continuous function of τ on $(0, 1) \cup (1, \infty)$.*

Finally, we note that our results give an answer for the case of dimension one of Problem 3 in Bugeaud and Laurent [5].

The paper is organized as follows. Some lemmas for the structure of uniform approximation set $\mathcal{U}_\tau[\theta]$ are stated in Section 2. The proof of Theorem 1 is given in Section 3. In Section 4 we discuss the set $\mathcal{U}_\tau[\theta]$ for $\tau = 1$ and prove Theorem 2. Section 5 is devoted to the proofs of Theorems 3 and 5. In the last section, we give the examples in which the bounds of Theorems 2 and 3 are attained.

2. CANTOR STRUCTURES

In this section, we first give some basic notations and properties on the continued fraction expansion of irrational numbers which will be useful later. Then we describe in detail the Cantor structure of the sets $\mathcal{U}_\tau[\theta]$.

Let $\theta \in [0, 1]$ be an irrational and $\{a_k\}_{k \geq 1}$ be the partial quotients of θ in its continued fraction expansion. The denominator q_k and the numerator p_k of the k -th convergent ($q_0 = 1, p_0 = 0$), satisfy the following facts

$$p_{n+1} = a_{n+1}p_n + p_{n-1}, \quad q_{n+1} = a_{n+1}q_n + q_{n-1}, \quad \forall n \geq 1. \quad (1)$$

A corresponding useful recurrence property is

$$\|q_{n-1}\theta\| = a_{n+1}\|q_n\theta\| + \|q_{n+1}\theta\|. \quad (2)$$

We also have the equality

$$q_{n+1}\|q_n\theta\| + q_n\|q_{n+1}\theta\| = 1, \quad (3)$$

and the estimation

$$\frac{1}{2q_{n+1}} < \frac{1}{q_{n+1} + q_n} < \|q_n\theta\| \leq \frac{1}{q_{n+1}}. \quad (4)$$

Recall that the irrationality exponent of θ is defined by $w(\theta) := \sup\{s > 0 : \liminf_{j \rightarrow \infty} j^s \|j\theta\| = 0\}$. By the theorem of best approximation (e.g. [34]), we can show that

$$w(\theta) = \limsup_{n \rightarrow \infty} \frac{\log q_{n+1}}{\log q_n}. \quad (5)$$

Since (q_n) is increasing, we have $w(\theta) \geq 1$ for every irrational number θ . The set of irrational numbers with $w(\theta) = 1$ has measure 1 and includes the set of irrational numbers with bounded partial quotients, which is of measure 0 and of Hausdorff

dimension 1. There exist numbers with $w(\theta) = \infty$, called the Liouville numbers. For more details on continued fractions, we refer to Khinchine's book [21].

In the following, we will investigate the Cantor structure of our main object $\mathcal{U}_\tau[\theta]$. Denote by $B(x, r)$ the open ball of center x and radius r in \mathbb{T} . Fix $\tau > 0$. Let

$$G_n = \bigcup_{i=1}^n B\left(i\theta, \frac{1}{n^\tau}\right) \quad \text{and} \quad F_k = \bigcap_{n=q_k+1}^{q_{k+1}} G_n.$$

Then we have

$$\mathcal{U}_\tau[\theta] = \bigcup_{\ell=1}^{\infty} \bigcap_{n=\ell}^{\infty} G_n = \bigcup_{\ell=1}^{\infty} \bigcap_{k=\ell}^{\infty} F_k.$$

We will calculate the Hausdorff dimension of $\bigcap_{k=1}^{\infty} F_k$. From the construction, we will see that for all ℓ , the Hausdorff dimensions of $\bigcap_{k=\ell}^{\infty} F_k$ are the same to that of $\bigcap_{k=1}^{\infty} F_k$. Thus by countable stability of the Hausdorff dimension,

$$\dim_H(\mathcal{U}_\tau[\theta]) = \dim_H\left(\bigcap_{k=1}^{\infty} F_k\right).$$

For $m \geq 1$, set

$$E_m := \bigcap_{k=1}^m F_k.$$

Then for each m , E_m is a union of intervals, and we have

$$\forall m \geq 1, \quad E_{m+1} \subset E_m, \quad \text{and} \quad \bigcap_{m=1}^{\infty} E_m = \bigcap_{k=1}^{\infty} F_k.$$

We are thus led to the calculation of the Hausdorff dimension of the nested Cantor set $\bigcap_{m=1}^{\infty} E_m$. To this end, let us first investigate the structure of F_k .

We note that $q_k\theta - p_k > 0$ if and only if k is even. In the following lemmas, we will consider only formulae of F_k for even k 's since for the odd k 's we will have symmetric formulae.

The well-known Three Step Theorem (e.g. [37]) shows that by the points $\{i\theta\}_{i=1}^{q_k}$, the unit circle \mathbb{T} is partitioned into q_k intervals of length $\|q_{k-1}\theta\|$ or $\|q_{k-1}\theta\| + \|q_k\theta\|$. Furthermore, for even k , we have

$$\mathbb{T} \setminus \{i\theta : 1 \leq i \leq q_k\} = \left(\bigcup_{i=1}^{q_{k-1}} (i\theta, (q_k - q_{k-1} + i)\theta) \right) \cup \left(\bigcup_{i=q_{k-1}+1}^{q_k} (i\theta, (i - q_{k-1})\theta) \right).$$

We remind that here and the follows, we will always consider $i\theta$ as a point in \mathbb{T} , but not in \mathbb{R} . So the sizes of these points are always less than 1. In particular, $q_k\theta = \|q_k\theta\|$ if k is even.

Lemma 6. (i) If

$$2 \left(\frac{1}{q_{k+1}} \right)^\tau > \|q_{k-1}\theta\| + \|q_k\theta\|, \quad (6)$$

then we have $F_k = \mathbb{T}$.

(ii) For the case of $\tau = 1$ and $a_{k+1} = 1$, we have $F_k = \mathbb{T}$.

Proof. (i) For each $q_k < n \leq q_{k+1}$ we have

$$2 \left(\frac{1}{n} \right)^\tau \geq 2 \left(\frac{1}{q_{k+1}} \right)^\tau > \|q_{k-1}\theta\| + \|q_k\theta\|.$$

Since any two neighboring points in $\{i\theta : 1 \leq i \leq q_k\}$ are distanced by $\|q_{k-1}\theta\|$ or $\|q_k\theta\| + \|q_{k-1}\theta\|$, all intervals overlap. Hence,

$$G_n = \bigcup_{i=1}^n B(i\theta, n^{-\tau}) = \mathbb{T}.$$

The result then follows.

(ii) If $a_{k+1} = 1$, then by (2) and (3) we have

$$\begin{aligned} q_{k+1} (\|q_{k-1}\theta\| + \|q_k\theta\|) &= q_{k+1} (2\|q_k\theta\| + \|q_{k+1}\theta\|) \\ &= 2q_{k+1}\|q_k\theta\| + (q_k + q_{k-1})\|q_{k+1}\theta\| \\ &= 2 - q_k\|q_{k+1}\theta\| + q_{k-1}\|q_{k+1}\theta\| < 2. \end{aligned}$$

Hence, by (i), if $\tau = 1$, $F_k = \mathbb{T}$. □

Lemma 7. For any $\tau \leq 1$, we have

(i)

$$F_k \supset \bigcup_{i=1}^{q_k} \left(i\theta - \left(\frac{1}{q_{k+1}} \right)^\tau, i\theta + r_k(i) \right),$$

where

$$\begin{aligned} r_k(i) &:= \min_{q_k < n \leq q_{k+1}} \left(\left\lfloor \frac{n-i}{q_k} \right\rfloor \|q_k\theta\| + \frac{1}{n^\tau} \right) \\ &\geq \min_{1 \leq c \leq a_{k+1}+1} \left((c-1)\|q_k\theta\| + \frac{1}{(cq_k + i - 1)^\tau} \right). \end{aligned}$$

(ii)

$$F_k \supset \bigcup_{i=1}^{q_k} \left(i\theta - \|q_k\theta\|, i\theta + \left(C_\tau \left(\frac{1}{q_k^\tau \|q_k\theta\|} \right)^{\frac{\tau}{\tau+1}} - 2 \right) \|q_k\theta\| \right),$$

where $C_\tau = \tau^{\frac{1}{\tau+1}} + \tau^{-\frac{\tau}{\tau+1}}$. Note that $1 < C_\tau \leq 2$.

(iii)

$$F_k \subset \bigcup_{i=1}^{q_k} \left(i\theta - \tau^{-\frac{\tau}{\tau+1}} \left(\frac{\|q_k\theta\|}{q_k} \right)^{\frac{\tau}{\tau+1}}, i\theta + C_\tau \left(\frac{\|q_k\theta\|}{q_k} \right)^{\frac{\tau}{\tau+1}} \right).$$

Proof. (i) Let n be an integer such that $q_k < n \leq q_{k+1}$ for some $k \in \mathbb{N}$. Then if k is even (the case when k is odd is the same up to symmetry), for each i with $1 \leq i \leq q_k$

$$\begin{aligned} G_n &= \bigcup_{j=1}^n B(j\theta, n^{-\tau}) \\ &\supset B\left(i\theta, \frac{1}{n^\tau}\right) \cup B\left((q_k + i)\theta, \frac{1}{n^\tau}\right) \cup \cdots \cup B\left(\left(\left\lfloor \frac{n-i}{q_k} \right\rfloor q_k + i\right)\theta, \frac{1}{n^\tau}\right). \end{aligned}$$

Notice that for $q_k < n \leq q_{k+1}$

$$\frac{1}{n^\tau} \geq \frac{1}{n} \geq \frac{1}{q_{k+1}} > \|q_k\theta\|. \quad (7)$$

Thus, the above $\left\lfloor \frac{n-i}{q_k} \right\rfloor$ intervals overlap and for each $1 \leq i \leq q_k$

$$G_n \supset \left(i\theta - \frac{1}{n^\tau}, i\theta + \left\lfloor \frac{n-i}{q_k} \right\rfloor q_k\theta + \frac{1}{n^\tau}\right).$$

Therefore, we have for each $1 \leq i \leq q_k$

$$\begin{aligned} F_k &= \bigcap_{n=q_k+1}^{q_{k+1}} G_n \supset \bigcap_{n=q_k+1}^{q_{k+1}} \left(i\theta - \frac{1}{n^\tau}, i\theta + \left\lfloor \frac{n-i}{q_k} \right\rfloor q_k\theta + \frac{1}{n^\tau}\right) \\ &= \left(i\theta - q_{k+1}^{-\tau}, i\theta + r_k(i)\right). \end{aligned}$$

For each $1 \leq i \leq q_k$, if $(c-1)q_k + i \leq n \leq cq_k + i - 1$, then

$$\left\lfloor \frac{n-i}{q_k} \right\rfloor \|q_k\theta\| + \frac{1}{n^\tau} \geq (c-1)\|q_k\theta\| + \frac{1}{(cq_k + i - 1)^\tau}.$$

Hence,

$$r_k(i) \geq \min_{1 \leq c \leq a_{k+1}+1} \left((c-1)\|q_k\theta\| + \frac{1}{(cq_k + i - 1)^\tau} \right). \quad (8)$$

(ii) By elementary calculus, when

$$x = \left(\frac{\tau}{q_k^\tau \|q_k\theta\|} \right)^{\frac{1}{\tau+1}},$$

the function $x \mapsto x\|q_k\theta\| + (xq_k)^{-\tau}$ has the minimum

$$\left(\tau^{\frac{1}{\tau+1}} + \tau^{-\frac{\tau}{\tau+1}} \right) \left(\frac{\|q_k\theta\|}{q_k} \right)^{\frac{\tau}{\tau+1}}.$$

Therefore, by (8) we have

$$\begin{aligned} r_k(i) &\geq \min_{1 \leq c \leq a_{k+1}+1} \left((c-1)\|q_k\theta\| + \frac{1}{((c+1)q_k)^\tau} \right) \\ &= \min_{1 \leq c \leq a_{k+1}+1} \left((c+1)\|q_k\theta\| + \frac{1}{((c+1)q_k)^\tau} \right) - 2\|q_k\theta\| \\ &\geq \left(\tau^{\frac{1}{\tau+1}} + \tau^{-\frac{\tau}{\tau+1}} \right) \left(\frac{\|q_k\theta\|}{q_k} \right)^{\frac{\tau}{\tau+1}} - 2\|q_k\theta\|. \end{aligned}$$

Hence, by (i) and (7), we have

$$F_k \supset \bigcup_{i=1}^{q_k} \left(i\theta - \|q_k\theta\|, i\theta + \left(\tau^{\frac{1}{\tau+1}} + \tau^{-\frac{\tau}{\tau+1}} \right) \left(\frac{\|q_k\theta\|}{q_k} \right)^{\frac{\tau}{\tau+1}} - 2\|q_k\theta\| \right).$$

(iii) Let

$$c = \left\lceil \left(\frac{\tau}{q_k^\tau \|q_k\theta\|} \right)^{\frac{1}{\tau+1}} \right\rceil.$$

We will distinguish two cases. If $c \leq a_{k+1}$, then we have

$$\begin{aligned} F_k &= \bigcap_{n=q_k+1}^{q_{k+1}} G_n \subset G_{cq_k} = \bigcup_{i=1}^{cq_k} B(i\theta, (cq_k)^{-\tau}) \\ &= \bigcup_{i=1}^{q_k} B(i\theta, (cq_k)^{-\tau}) \cup B((q_k+i)\theta, (cq_k)^{-\tau}) \cup \dots \cup B(((c-1)q_k+i)\theta, (cq_k)^{-\tau}). \end{aligned}$$

Since

$$\left(\frac{1}{cq_k} \right)^\tau \geq \frac{1}{cq_k} \geq \frac{1}{a_{k+1}q_k} \geq \frac{1}{q_{k+1}} > \|q_k\theta\|,$$

the above c intervals in the union overlap and we have

$$F_k \subset \bigcup_{i=1}^{q_k} (i\theta - (cq_k)^{-\tau}, i\theta + (c-1)q_k\theta + (cq_k)^{-\tau}).$$

By the definition of c , we have

$$\begin{aligned} F_k &\subset \bigcup_{i=1}^{q_k} \left(i\theta - \left(\frac{\tau q_k}{\|q_k\theta\|} \right)^{-\frac{\tau}{\tau+1}}, i\theta + \frac{1}{q_k} \left(\frac{\tau q_k}{\|q_k\theta\|} \right)^{\frac{1}{\tau+1}} \|q_k\theta\| + \left(\frac{\tau q_k}{\|q_k\theta\|} \right)^{-\frac{\tau}{\tau+1}} \right) \\ &= \bigcup_{i=1}^{q_k} \left(i\theta - \tau^{-\frac{\tau}{\tau+1}} \left(\frac{\|q_k\theta\|}{q_k} \right)^{\frac{\tau}{\tau+1}}, i\theta + \left(\tau^{\frac{1}{\tau+1}} + \tau^{-\frac{\tau}{\tau+1}} \right) \left(\frac{\|q_k\theta\|}{q_k} \right)^{\frac{\tau}{\tau+1}} \right). \end{aligned}$$

Then the assertion follows.

If $c > a_{k+1}$, i.e.,

$$\left(\frac{\tau}{q_k^\tau \|q_k\theta\|} \right)^{\frac{1}{\tau+1}} > a_{k+1},$$

then we have

$$\begin{aligned} \left(\tau^{\frac{1}{\tau+1}} + 2\tau^{-\frac{\tau}{\tau+1}} \right) \left(\frac{\|q_k\theta\|}{q_k} \right)^{\frac{\tau}{\tau+1}} &> \left(\tau^{\frac{1}{\tau+1}} + 2\tau^{-\frac{\tau}{\tau+1}} \right) a_{k+1} \left(\frac{\|q_k\theta\|^{\tau+1}}{\tau} \right)^{\frac{1}{\tau+1}} \\ &= (1 + 2/\tau) a_{k+1} \|q_k\theta\| \geq 3a_{k+1} \|q_k\theta\| \\ &> \|q_{k-1}\theta\| + \|q_k\theta\|. \end{aligned}$$

Thus,

$$\bigcup_{i=1}^{q_k} \left(i\theta - \tau^{-\frac{\tau}{\tau+1}} \left(\frac{\|q_k\theta\|}{q_k} \right)^{\frac{\tau}{\tau+1}}, i\theta + \left(\tau^{\frac{1}{\tau+1}} + \tau^{-\frac{\tau}{\tau+1}} \right) \left(\frac{\|q_k\theta\|}{q_k} \right)^{\frac{\tau}{\tau+1}} \right) = \mathbb{T},$$

and the assertion trivially holds. \square

Lemma 8. *Suppose that $\tau > 1$.*

(i) *We have*

$$\bigcup_{i=1}^{q_k} B(i\theta, q_{k+1}^{-\tau}) \subset F_k \subset \bigcup_{i=1}^{q_{k+1}} B(i\theta, q_{k+1}^{-\tau})$$

and for large q_k the balls $B(i\theta, q_{k+1}^{-\tau})$, $1 \leq i \leq q_{k+1}$, are disjoint.

(ii) *If $q_{k+1}^{-\tau} + q_k^{-\tau} \leq \|q_k\theta\|$, then*

$$F_k = \bigcup_{i=1}^{q_k} B(i\theta, q_{k+1}^{-\tau}).$$

(iii) *For large q_k*

$$\bigcup_{i=1}^{\max(c_k, 1) \cdot q_k} B(i\theta, q_{k+1}^{-\tau}) \subset F_k \subset \bigcup_{i=1}^{(c_k+2)q_k} B(i\theta, q_{k+1}^{-\tau}).$$

where $c_k := \left\lfloor (\|q_k\theta\| q_k^\tau)^{-1/(\tau+1)} \right\rfloor$.

Proof. (i) For each $1 \leq i \leq q_k$ and $q_k < n \leq q_{k+1}$,

$$B(i\theta, q_{k+1}^{-\tau}) \subset \bigcup_{j=1}^n B(j\theta, n^{-\tau}).$$

Thus,

$$\bigcup_{i=1}^{q_k} B(i\theta, q_{k+1}^{-\tau}) \subset \bigcap_{n=q_k+1}^{q_{k+1}} \left(\bigcup_{j=1}^n B(j\theta, n^{-\tau}) \right) = F_k.$$

On the other side,

$$F_k = \bigcap_{n=q_k+1}^{q_{k+1}} \left(\bigcup_{i=1}^n B(i\theta, n^{-\tau}) \right) \subset \bigcup_{i=1}^{q_{k+1}} B(i\theta, q_{k+1}^{-\tau}). \quad (9)$$

Since $\tau > 1$, for large q_k (hence for larger q_{k+1}),

$$2q_{k+1}^\tau < q_{k+1}^{-1} < \|q_k\theta\|. \quad (10)$$

Thus, the balls $B(i\theta, q_{k+1}^{-\tau})$, $1 \leq i \leq q_{k+1}$, are disjoint.

(ii) Suppose that there exists $x \in F_k \setminus \bigcup_{i=1}^{q_k} B(i\theta, q_{k+1}^{-\tau})$. By (i), we have $x \in B(j\theta, q_{k+1}^{-\tau})$ for some $q_k + 1 \leq j \leq q_{k+1}$. Since $x \in G_{q_{k+1}} \subset F_k$, there exists $1 \leq i \leq q_k$ such that $x \in B(i\theta, q_k^{-\tau})$. Since $|i\theta - j\theta| \leq \|q_k\theta\|$ and $x \in B(j\theta, q_{k+1}^{-\tau}) \cap B(i\theta, q_k^{-\tau}) \neq \emptyset$, we have $\|q_k\theta\| < q_k^{-\tau} + q_{k+1}^{-\tau}$, which is a contradiction.

(iii) Let

$$c_k = \left\lfloor (\|q_k\theta\| q_k^\tau)^{-1/(\tau+1)} \right\rfloor.$$

Suppose $c_k \geq 2$. Then for $1 \leq m \leq c_k - 1$, and for large q_k ,

$$\begin{aligned} m\|q_k\theta\| &\leq \left((\|q_k\theta\|q_k^\tau)^{-1/(\tau+1)} - 1 \right) \|q_k\theta\| = \left(\frac{\|q_k\theta\|}{q_k} \right)^{\frac{\tau}{\tau+1}} - \|q_k\theta\| \\ &\leq \frac{1}{(c_k q_k)^\tau} - \frac{1}{(q_{k+1})^\tau} \leq \frac{1}{((c_k - m + 1)q_k)^\tau} - \frac{1}{(q_{k+1})^\tau}, \end{aligned} \quad (11)$$

where for the second inequality we use (10).

Let i be an integer satisfying $q_k < i \leq c_k q_k$. For each n with $q_k \leq n < i$, choose m as $i - m q_k \leq n < i - (m - 1)q_k$ ($1 \leq m \leq c_k - 1$). Then by (11) we have

$$\begin{aligned} B(i\theta, q_{k+1}^{-\tau}) &\subset B((i - m q_k)\theta, ((c_k - m + 1)q_k)^{-\tau}) \\ &\subset B((i - m q_k)\theta, (i - (m - 1)q_k)^{-\tau}) \\ &\subset B((i - m q_k)\theta, n^{-\tau}) \subset \bigcup_{j=1}^n B(j\theta, n^{-\tau}). \end{aligned}$$

We also have for $i \leq n \leq q_{k+1}$,

$$B(i\theta, q_{k+1}^{-\tau}) \subset \bigcup_{j=1}^n B(j\theta, n^{-\tau}).$$

Therefore, for $q_k < i \leq c_k q_k$,

$$B(i\theta, q_{k+1}^{-\tau}) \subset \bigcap_{n=q_k+1}^{q_{k+1}} \left(\bigcup_{j=1}^n B(j\theta, n^{-\tau}) \right) = F_k.$$

Hence, if $c_k \geq 2$, we have

$$\bigcup_{i=q_k+1}^{c_k q_k} B(i\theta, q_{k+1}^{-\tau}) \subset F_k. \quad (12)$$

On the other hand, we have already proved in (i) that

$$\bigcup_{i=1}^{q_k} B(i\theta, q_{k+1}^{-\tau}) \subset F_k.$$

Then the first inclusion in (iii) follows.

For $m \geq c_k + 2$, and for large q_k ,

$$\begin{aligned} m\|q_k\theta\| &> \left((\|q_k\theta\|q_k^\tau)^{-1/(\tau+1)} + 1 \right) \|q_k\theta\| = \left(\frac{\|q_k\theta\|}{q_k} \right)^{\frac{\tau}{\tau+1}} + \|q_k\theta\| \\ &> \frac{1}{((c_k + 1)q_k)^\tau} + \frac{1}{(q_{k+1})^\tau}. \end{aligned}$$

Therefore, if $(c_k + 2)q_k < i \leq q_{k+1}$, then for any m with $i - m q_k > 0$

$$B(i\theta, q_{k+1}^{-\tau}) \cap B((i - m q_k)\theta, (i - q_k)^{-\tau}) = \emptyset.$$

Choose $n = i - q_k$. Then

$$B(i\theta, q_{k+1}^{-\tau}) \cap \left(\bigcup_{j=1}^n B(j\theta, n^{-\tau}) \right) = \emptyset.$$

Hence,

$$B(i\theta, q_{k+1}^{-\tau}) \cap F_k = \emptyset.$$

Therefore, by (9) we have

$$F_k \subset \bigcup_{i=1}^{(c_k+2)q_k} B(i\theta, q_{k+1}^{-\tau}), \quad (13)$$

which is the second inclusion in (iii). \square

3. PROOF OF THEOREM 1

We will use the following known facts in fractal geometry to calculate the Hausdorff dimensions. Let $E_0 \supset E_1 \supset E_2 \supset \dots$ be a decreasing sequence of sets, with each E_n a union of finite number of disjoint intervals. Set

$$F = \bigcap_{n=0}^{\infty} E_n.$$

Fact 9 ([12], p.64). *Suppose each interval of E_{i-1} contains at least m_i intervals of E_i ($i = 1, 2, \dots$) which are separated by gaps of at least ε_i , where $0 < \varepsilon_{i+1} < \varepsilon_i$ for each i . Then*

$$\dim_H(F) \geq \underline{\lim}_{i \rightarrow \infty} \frac{\log(m_1 \cdots m_{i-1})}{-\log(m_i \varepsilon_i)}.$$

Fact 10 ([12], p.59). *Suppose F can be covered by ℓ_i sets of diameter at most δ_i with $\delta_i \rightarrow 0$ as $i \rightarrow \infty$. Then*

$$\dim_H(F) \leq \underline{\lim}_{i \rightarrow \infty} \frac{\log \ell_i}{-\log \delta_i}.$$

Now we are ready to prove Theorem 1. Recall that

$$F_k = \bigcap_{n=q_k+1}^{q_{k+1}} \left(\bigcup_{i=1}^n B(i\theta, n^{-\tau}) \right).$$

By the discussion at the beginning of Section 2, we need to calculate the Hausdorff dimension of the set

$$F = \bigcap_{n=1}^{\infty} E_n, \quad \text{with } E_n = \bigcap_{k=1}^n F_k.$$

The dimension of F is the same to that of $\mathcal{U}_\tau[\theta]$.

Proof of Theorem 1. (i) If $\tau < 1/w(\theta)$, by (5) we have for all large k ,

$$2 \left(\frac{1}{q_{k+1}} \right)^\tau > \frac{2}{q_k} > \frac{1}{q_k} + \frac{1}{q_{k+1}} \geq \|q_{k-1}\theta\| + \|q_k\theta\|.$$

Thus by Lemma 6, for all large k , F_k is the whole circle \mathbb{T} . Hence,

$$\mathcal{U}_\tau[\theta] = \bigcup_{\ell=1}^{\infty} \bigcap_{k=\ell}^{\infty} F_k = \mathbb{T}.$$

(ii) If $\tau > w(\theta)$, then we have $q_k^\tau \|q_k\theta\| > 2$ for all large k . Hence, $q_{k+1}^{-\tau} + q_k^{-\tau} \leq 2q_k^{-\tau} \leq \|q_k\theta\|$ for large k . By Lemma 8 (ii), for large k

$$F_k = \bigcup_{i=1}^{q_k} B(i\theta, q_{k+1}^{-\tau}).$$

Thus,

$$\mathcal{U}_\tau[\theta] = \bigcup_{\ell=1}^{\infty} \bigcap_{k=\ell}^{\infty} F_k = \{i\theta : i \geq 1\}.$$

(iii) Assume that $1/w(\theta) < \tau < 1$. If $q_k \|q_k\theta\|^\tau \geq 1$ then we have

$$\begin{aligned} 2 \left(\frac{1}{q_{k+1}} \right)^\tau &> 2 \|q_k\theta\|^\tau \geq \|q_k\theta\|^\tau + \|q_k\theta\| \\ &\geq \frac{1}{q_k} + \|q_k\theta\| > \|q_{k-1}\theta\| + \|q_k\theta\|. \end{aligned}$$

By Lemma 6, we have $F_k = \mathbb{T}$. Thus we only consider F_k such that $q_k \|q_k\theta\|^\tau < 1$.

Suppose for some k

$$q_k \|q_k\theta\|^\tau < 1. \quad (14)$$

Then

$$\frac{1}{4} \left(\frac{\|q_k\theta\|}{q_k} \right)^{\frac{\tau}{\tau+1}} < \frac{1}{4q_k} < \frac{1}{2} \|q_{k-1}\theta\|. \quad (15)$$

Put

$$\tilde{F}_k(i) := \left(i\theta - \|q_k\theta\|, i\theta + \frac{1}{4} \left(\frac{\|q_k\theta\|}{q_k} \right)^{\frac{\tau}{\tau+1}} - \|q_k\theta\| \right).$$

By (14), for large k

$$\|q_k\theta\| < q_k^{-1/\tau} \ll q_k^{-\tau},$$

and hence

$$\left(\frac{\|q_k\theta\|}{q_k} \right)^{\frac{\tau}{\tau+1}} \ll \left(\frac{1}{q_k^\tau \|q_k\theta\|} \right)^{\frac{\tau}{\tau+1}} \|q_k\theta\|. \quad (16)$$

By (14), we also have

$$\frac{1}{q_k^\tau \|q_k\theta\|} > \frac{1}{\|q_k\theta\|^{1-\tau^2}} \rightarrow \infty, \quad \text{as } k \rightarrow \infty. \quad (17)$$

Since $C_\tau > 1$, by (16), (17) and Lemma 7 (ii)

$$\tilde{F}_k(i) \subset F_k. \quad (18)$$

By (15), the intervals in $\tilde{F}_k(i)$'s are disjoint and distanced by more than $\frac{1}{2}\|q_{k-1}\theta\|$.

We estimate the number of subintervals of $\tilde{F}_{k+\ell}$ in \tilde{F}_k by the Denjoy-Koksma inequality (see, e.g., [18]): let T be an irrational rotation by θ and f be a real valued function of bounded variation on the unit interval. Then for any x

$$\left| \sum_{n=0}^{q_k-1} f(T^n x) - q_k \int f d\mu \right| \leq \text{var}(f). \quad (19)$$

For a given interval I , by the Denjoy-Koksma inequality (19), we have

$$\#\{1 \leq n \leq q_k : n\theta \in I\} = \sum_{n=0}^{q_k-1} 1_I(T^n x) \geq q_k \mu(I) - 2.$$

Since $\tilde{F}_{k+\ell}$ consists of the disjoint intervals at $q_{k+\ell}$ orbital points, if $q_{k+\ell}\|q_{k+\ell}\theta\|^\tau < 1$, $\ell \geq 1$, we have for each i

$$\begin{aligned} & \#\{1 \leq n \leq q_{k+\ell} : \tilde{F}_{k+\ell}(n) \subset \tilde{F}_k(i)\} \\ & \geq q_{k+\ell} \left(\frac{1}{4} \left(\frac{\|q_k\theta\|}{q_k} \right)^{\frac{\tau}{\tau+1}} - \frac{1}{4} \left(\frac{\|q_{k+\ell}\theta\|}{q_{k+\ell}} \right)^{\frac{\tau}{\tau+1}} \right) - 2 \\ & \geq q_{k+\ell} \left(\frac{1}{4} \left(\frac{\|q_k\theta\|}{q_k} \right)^{\frac{\tau}{\tau+1}} - \frac{1}{2} \|q_{k+\ell-1}\theta\| - \frac{2}{q_{k+\ell}} \right) \\ & \geq q_{k+\ell} \left(\frac{1}{4} \left(\frac{\|q_k\theta\|}{q_k} \right)^{\frac{\tau}{\tau+1}} - 5 \|q_k\theta\| \right). \end{aligned}$$

Noticing the fact that for k large enough

$$\left(\frac{\|q_k\theta\|}{q_k} \right)^{\frac{\tau}{\tau+1}} = \left(\frac{1}{q_k^\tau \|q_k\theta\|} \right)^{\frac{1}{\tau+1}} \|q_k\theta\| > \left(q_k^{1-\tau} \right)^{\frac{1}{\tau+1}} \|q_k\theta\| > 100 \|q_k\theta\|,$$

we deduce that

$$\#\{1 \leq n \leq q_{k+\ell} : \tilde{F}_{k+\ell}(n) \subset \tilde{F}_k(i)\} \geq \frac{q_{k+\ell}}{5} \left(\frac{\|q_k\theta\|}{q_k} \right)^{\frac{\tau}{\tau+1}}.$$

Let $\{n_i\}$ be the sequence of all integers satisfying

$$n_i \|n_i\theta\|^\tau < 1.$$

We remark that since $1/w(\theta) < \tau$, by the definition of $w(\theta)$, there are infinitely many such n_i 's. Further, by Legendre's theorem ([30], pp. 27–29), we have $n_i = q_{k_i}$ for some k_i .

Since $F_k = \mathbb{T}$ if $k \neq k_i$, the Cantor set F is

$$F = \bigcap_{k=1}^{\infty} F_k = \bigcap_{i=1}^{\infty} F_{k_i}.$$

Now we will apply Fact 9. Let

$$E_i := \bigcap_{j=1}^i F_{k_j}.$$

Then $F = \bigcap_{i=1}^{\infty} E_i$. Keeping the notations m_i, ε_i as in Fact 9, we have for i large enough,

$$m_i \geq \frac{q_{k_i}}{5} \left(\frac{\|q_{k_{i-1}}\theta\|}{q_{k_{i-1}}} \right)^{\frac{\tau}{\tau+1}}, \quad \varepsilon_i \geq \frac{1}{2} \|q_{k_{i-1}}\theta\|. \quad (20)$$

Since the lower limit will not be changed if we modify finite number of m_i and ε_i 's, we can suppose that the estimates (20) hold for all i . Hence, by Fact 9

$$\begin{aligned} \dim_H(F) &\geq \liminf_i \frac{\log(m_1 \cdots m_i)}{-\log(m_{i+1}\varepsilon_{i+1})} \\ &\geq \liminf_i \frac{\frac{\tau}{\tau+1} \log\left(\frac{\|n_1\theta\| \cdots \|n_{i-1}\theta\|}{n_1 \cdots n_{i-1}}\right) + \log(n_1 \cdots n_i) - i \log 5}{\frac{\tau}{\tau+1} \log(n_i/\|n_i\theta\|)} \\ &= \liminf_i \frac{\tau \log(\|n_1\theta\| \cdots \|n_{i-1}\theta\|) + \log(n_1 \cdots n_{i-1}) + (\tau+1) \log n_i}{\tau \log(n_i/\|n_i\theta\|)}. \end{aligned}$$

The last equality follows from the fact that n_k increases super-exponentially when $w(\theta) > 1$.

For the other side, by Lemma 7 (iii), we have

$$\begin{aligned} F_k &\subset \bigcup_{i=1}^{q_k} \left(i\theta - C_\tau \left(\frac{\|q_k\theta\|}{q_k} \right)^{\frac{\tau}{\tau+1}}, i\theta + C_\tau \left(\frac{\|q_k\theta\|}{q_k} \right)^{\frac{\tau}{\tau+1}} \right) \\ &= \bigcup_{i=1}^{q_k} \left(i\theta - C_\tau \left(\frac{1}{q_k^\tau \|q_k\theta\|} \right)^{\frac{1}{\tau+1}} \|q_k\theta\|, i\theta + C_\tau \left(\frac{1}{q_k^\tau \|q_k\theta\|} \right)^{\frac{1}{\tau+1}} \|q_k\theta\| \right). \end{aligned}$$

Thus F_{k_i} , hence E_{k_i} can be covered by ℓ_i sets of diameter at most δ_i , with

$$\begin{aligned} \ell_i &\leq \left(2C_\tau \left(\frac{1}{q_{k_1}^\tau \|q_{k_1}\theta\|} \right)^{\frac{1}{\tau+1}} + 2 \right) \cdots \left(2C_\tau \left(\frac{1}{q_{k_{i-1}}^\tau \|q_{k_{i-1}}\theta\|} \right)^{\frac{1}{\tau+1}} + 2 \right), \\ \delta_i &\leq 2C_\tau \left(\frac{\|q_{k_i}\theta\|}{q_{k_i}} \right)^{\frac{\tau}{\tau+1}}. \end{aligned}$$

Since $x+1 \leq 2x$ for $x \geq 1$ and $C_\tau > 1$, we have

$$\ell_i \leq (4C_\tau)^{i-1} \left(\frac{1}{\|n_1\theta\| n_1^\tau} \cdots \frac{1}{\|n_{i-1}\theta\| n_{i-1}^\tau} \right)^{\frac{1}{\tau+1}}, \quad \delta_i \leq 2C_\tau \left(\frac{\|n_i\theta\|}{n_i} \right)^{\frac{\tau}{\tau+1}}.$$

Hence, by Fact 10, and $\|q_{k_{i-1}}\theta\|^{-1} \leq 2q_{k_i}$, we have

$$\begin{aligned} \dim_H(F) &\leq \liminf_i \frac{\log \ell_i}{-\log \delta_i} \\ &\leq \liminf_i \frac{\tau \log(\|n_1\theta\| \cdots \|n_{i-1}\theta\|) + \log(n_1 \cdots n_{i-1}) + (\tau+1) \log n_i}{\tau \log(n_i/\|n_i\theta\|)}. \end{aligned}$$

(iv) Suppose $1 < \tau < w(\theta)$. If

$$q_k^\tau \|q_k \theta\| \geq 2,$$

then

$$q_{k+1}^{-\tau} + q_k^{-\tau} \leq 2q_k^{-\tau} \leq \|q_k \theta\|.$$

By Lemma 8 (ii)

$$F_k = \bigcup_{i=1}^{q_k} B(i\theta, q_{k+1}^{-\tau}).$$

Let $\{n_i\}$ be the sequence of all integers satisfying

$$n_i^\tau \|n_i \theta\| < 2.$$

Remark that by the definition of $w(\theta)$, there are infinitely many such n_i 's. Applying Legendre's theorem ([30], pp. 27-29), we have $n_i = q_{k_i}$ for some k_i . Since $F_k = \bigcup_{i=1}^{q_k} B(i\theta, q_{k+1}^{-\tau})$ if $k \neq k_i$, we have

$$\bigcap_{\ell=k_{i-1}+1}^{k_i-1} F_\ell = \bigcup_{i=1}^{q_{k_{i-1}+1}} B(i\theta, q_{k_i}^{-\tau}),$$

and thus

$$\bigcap_{\ell=k_{i-1}+1}^{k_i} F_\ell = F_{k_i}.$$

Take $E_i := \bigcap_{j=1}^j F_{k_j}$. Then

$$F = \bigcap_{i=1}^{\infty} E_i.$$

In the same way as the above proofs of (ii) of Theorem 1, we can deduce by applying Lemma 8 (iii) that

$$m_i \geq \max\left(\left[\left(\|q_{k_i} \theta\| q_{k_i}^\tau\right)^{-1/(\tau+1)}\right], 1\right) \quad \text{and} \quad \epsilon_i \geq \|q_{k_i} \theta\| - \frac{2}{(q_{k_i+1})^\tau}.$$

Note

$$\left(\|q_{k_i} \theta\| q_{k_i}^\tau\right)^{-1/(\tau+1)} > 2^{-1/(\tau+1)} > 2^{-1/2}.$$

Since $\max(\lfloor x \rfloor, 1) > \frac{x}{2}$ for any real $x > 2^{-1/2}$, we have

$$m_i \geq \frac{1}{2} \left(\frac{1}{\|q_{k_i} \theta\| q_{k_i}^\tau} \right)^{\frac{1}{\tau+1}}.$$

For large i , from $\tau > 1$, we deduce

$$\epsilon_i \geq \|q_{k_i} \theta\| - \frac{2}{(q_{k_i+1})^\tau} \geq \frac{\|q_{k_i} \theta\|}{2}.$$

Therefore, by Fact 9

$$\begin{aligned} \dim_H(F) &\geq \liminf_i \frac{\log(m_1 \cdots m_{i-1})}{-\log(m_i \varepsilon_i)} \\ &\geq \liminf_k \frac{-\frac{\tau}{\tau+1} \log(n_1 \|n_1 \theta\|^{1/\tau} n_2 \|n_2 \theta\|^{1/\tau} \cdots n_{i-1} \|n_{i-1} \theta\|^{1/\tau}) - (i-1) \log 2}{\frac{\tau}{\tau+1} \log(n_i / \|n_i \theta\|) + \log 4} \\ &= \liminf_k \frac{-\log(n_1 \|n_1 \theta\|^{1/\tau} n_2 \|n_2 \theta\|^{1/\tau} \cdots n_{i-1} \|n_{i-1} \theta\|^{1/\tau})}{\log(n_i / \|n_i \theta\|)}. \end{aligned}$$

For the upper bound, by Lemma 8 (iii)

$$\begin{aligned} \ell_i &\leq \left(\left(\frac{1}{\|n_1 \theta\| n_1^\tau} \right)^{\frac{1}{\tau+1}} + 2 \right) \cdots \left(\left(\frac{1}{\|n_{i-1} \theta\| n_{i-1}^\tau} \right)^{\frac{1}{\tau+1}} + 2 \right), \\ \delta_i &\leq \left(\left(\frac{1}{\|n_i \theta\| n_i^\tau} \right)^{\frac{1}{\tau+1}} + 2 \right) \cdot \|n_i \theta\|. \end{aligned}$$

Since $x + 2 \leq 3x$ for $x \geq 1$, we have

$$\ell_i \leq 3^{i-1} \left(\frac{1}{\|n_1 \theta\| n_1^\tau} \cdots \frac{1}{\|n_{i-1} \theta\| n_{i-1}^\tau} \right)^{\frac{1}{\tau+1}}, \quad \delta_i \leq 3 \left(\frac{\|n_i \theta\|}{n_i} \right)^{\frac{\tau}{\tau+1}}.$$

Thus by Fact 10,

$$\begin{aligned} \dim_H(F) &\leq \liminf_i \frac{\log \ell_i}{-\log \delta_i} \\ &\leq \liminf_i \frac{-\log(n_1 \|n_1 \theta\|^{1/\tau} n_2 \|n_2 \theta\|^{1/\tau} \cdots n_{i-1} \|n_{i-1} \theta\|^{1/\tau}) + (i-1) \log 3}{\log(n_i / \|n_i \theta\|) - \log 3} \\ &= \liminf_i \frac{-\log(n_1 \|n_1 \theta\|^{1/\tau} n_2 \|n_2 \theta\|^{1/\tau} \cdots n_{i-1} \|n_{i-1} \theta\|^{1/\tau})}{\log(n_i / \|n_i \theta\|)}. \end{aligned}$$

The last equality is from the super-exponentially increasing of n_k when $w(\theta) > 1$. \square

4. THE CASE OF $\tau = 1$ AND PROOF OF THEOREM 2

For the case of $\tau = 1$, we need more accurate estimation on the size of intervals of F_k .

Lemma 11. *If $\frac{1}{(b+1)(b+2)} \leq q_k \|q_k \theta\| < \frac{1}{b(b+1)}$, $b \geq 1$, then*

$$\bigcup_{1 \leq i \leq q_k} \left(i\theta - \frac{1}{q_{k+1}}, i\theta + (b-1)q_k \theta + \frac{1}{(b+1)q_k} \right) \subset F_k.$$

Proof. Since $\frac{1}{(b+1)(b+2)q_k} \leq \|q_k \theta\| < \frac{1}{b(b+1)q_k}$, for any integer $c \geq 1$

$$(b-c)\|q_k \theta\| + \frac{1}{(b+1)q_k} - \frac{1}{(c+1)q_k} = (b-c) \left(\|q_k \theta\| - \frac{1}{(b+1)(c+1)q_k} \right) \leq 0.$$

Therefore, for all $c \geq 1$ and $1 \leq i \leq q_k$

$$(b-1)\|q_k\theta\| + \frac{1}{(b+1)q_k} \leq (c-1)\|q_k\theta\| + \frac{1}{(c+1)q_k} \leq (c-1)\|q_k\theta\| + \frac{1}{cq_k+i}.$$

Applying Lemma 7 (i), we complete the proof. \square

For each $k \geq 0$, denote

$$r_{k+1} := \begin{cases} \left\lfloor \sqrt{4a_{k+1}+5} \right\rfloor - 3, & a_{k+1} \neq 2, \\ 1, & a_{k+1} = 2. \end{cases}$$

We remark that $0 \leq r_{k+1} < a_{k+1}$. Further, elementary calculations immediately give us bounds for r_{k+1} as follows:

$$r_{k+1} + 1 \geq \sqrt{a_{k+1}+1} > \sqrt{\frac{q_{k+1}}{q_k}} \quad \text{for } a_{k+1} \neq 4, \quad (21)$$

$$r_{k+1} + \frac{3}{2} \geq \sqrt{a_{k+1}+1} + \frac{1}{2\sqrt{a_{k+1}+1}} > \sqrt{\frac{q_{k+1}}{q_k}} + \frac{1}{2}\sqrt{\frac{q_k}{q_{k+1}}}, \quad (22)$$

$$r_{k+1} + 1 \geq \frac{1}{\sqrt{2}} \left(\sqrt{a_{k+1}+1} + \frac{1}{2\sqrt{a_{k+1}+1}} \right) > \frac{1}{\sqrt{2}} \left(\sqrt{\frac{q_{k+1}}{q_k}} + \frac{1}{2}\sqrt{\frac{q_k}{q_{k+1}}} \right). \quad (23)$$

Define inductively

$$\tilde{r}_{k+1} := \begin{cases} r_{k+1} + 1 = 2, & \text{if } a_{k+1} = 4 \text{ and } a_{k+2} \geq 2, \\ r_{k+1}, & \text{otherwise.} \end{cases}$$

Then for $a_{k+1} \neq 4$ or $a_{k+2} \geq 2$ (i.e., for all cases except $a_{k+1} = 4, a_{k+2} = 1$)

$$\tilde{r}_{k+1} + 1 \geq \sqrt{a_{k+1}+1} \geq \sqrt{\frac{q_{k+1}}{q_k}}. \quad (24)$$

It is not difficult to check that for $a_{k+1} \geq 2$

$$\tilde{r}_{k+1} \leq \frac{a_{k+1}}{2}. \quad (25)$$

Lemma 12. *For all $k \geq 1$, we have*

$$\bigcup_{i=1}^{q_k} (i\theta - \|q_k\theta\|, i\theta + r_{k+1}\|q_k\theta\| + \|q_{k+1}\theta\|) \subset F_k.$$

Moreover, for each $k \geq 1$

$$\begin{cases} \bigcup_{i=1}^{q_k} (i\theta - \|q_k\theta\|, i\theta + \tilde{r}_{k+1}\|q_k\theta\| + \|q_{k+1}\theta\|) \subset F_k, & \text{if } a_k = 1, \\ \bigcup_{i=1}^{(\tilde{r}_k+1)q_{k-1}} (i\theta - \|q_k\theta\|, i\theta + \tilde{r}_{k+1}\|q_k\theta\| + \|q_{k+1}\theta\|) \subset F_k, & \text{if } a_k \geq 2. \end{cases}$$

Proof. For the first part of the proof, we distinguish three cases.

(i) If $a_{k+1} = 1$, then by Lemma 6, we have $F_k = \mathbb{T}$.

(ii) Suppose $a_{k+1} = 2$. Then $\frac{1}{4} < q_k \|q_k \theta\| < \frac{1}{2}$. Thus, by applying Lemma 11 for $b = 1$, we have

$$\bigcup_{1 \leq i \leq q_k} \left(i\theta - \frac{1}{q_{k+1}}, i\theta + \frac{1}{2q_k} \right) \subset F_k. \quad (26)$$

Using the equality (3) for $n = k - 1$, and observing $q_{k+1} = a_{k+1}q_k + q_{k-1} = 2q_k + q_{k-1}$, we have

$$\begin{aligned} \frac{1}{2q_k} + \frac{1}{q_{k+1}} &= \frac{1}{q_k} - \left(\frac{1}{2q_k} - \frac{1}{q_{k+1}} \right) \\ &= \frac{q_k \|q_{k-1} \theta\| + q_{k-1} \|q_k \theta\|}{q_k} - \frac{q_{k+1} - 2q_k}{2q_k q_{k+1}} \\ &= \|q_{k-1} \theta\| + \frac{q_{k-1}}{q_k} \left(\|q_k \theta\| - \frac{1}{2q_{k+1}} \right) > \|q_{k-1} \theta\|. \end{aligned}$$

Then by (26), for $q_{k-1} < i \leq q_k$

$$\begin{aligned} &(i\theta - \|q_k \theta\|, i\theta + \|q_k \theta\| + \|q_{k+1} \theta\|) \\ &\subset \left(i\theta - \frac{1}{q_{k+1}}, i\theta + \frac{1}{2q_k} \right) \cup \left((i - q_{k-1})\theta - \frac{1}{q_{k+1}}, (i - q_{k-1})\theta + \frac{1}{2q_k} \right) \subset F_k. \end{aligned} \quad (27)$$

On the other hand, by (3), and the assumption $a_{k+1} = 2$, we can check

$$\|q_k \theta\| + \|q_{k+1} \theta\| < \frac{1}{q_k + q_{k-1}}, \quad \|q_{k+1} \theta\| < \frac{1}{2q_k + q_{k-1}}.$$

Thus, for $1 \leq i \leq q_{k-1}$

$$\begin{aligned} &(i\theta - \|q_k \theta\|, i\theta + \|q_k \theta\| + \|q_{k+1} \theta\|) \\ &\subset \left(i\theta - \frac{1}{q_{k+1}}, i\theta + \min \left(\frac{1}{q_k + q_{k-1}}, \|q_k \theta\| + \frac{1}{2q_k + q_{k-1}} \right) \right) \subset F_k, \end{aligned} \quad (28)$$

where the second inclusion is from Lemma 7 (i).

Combining (27) and (28), we conclude that for $a_{k+1} = 2$

$$\bigcup_{1 \leq i \leq q_k} (i\theta - \|q_k \theta\|, i\theta + \|q_k \theta\| + \|q_{k+1} \theta\|) \subset F_k.$$

(iii) Assume $a_{k+1} \geq 3$. There exists an integer $b \geq 1$ satisfying

$$b(b+1) < \frac{1}{q_k \|q_k \theta\|} \leq (b+1)(b+2).$$

Thus, we have $b(b+1) - 1 \leq a_{k+1} \leq (b+1)(b+2) - 1$. We will apply Lemma 11 and we will distinguish three parts according to the value of a_{k+1} .

If $b^2 + b - 1 \leq a_{k+1} \leq b^2 + 2b - 1$, then $\lfloor \sqrt{4a_{k+1} + 5} \rfloor = 2b + 1$ and

$$(2b - 2) \|q_k \theta\| + \|q_{k+1} \theta\| < (b - 1) \|q_k \theta\| + \frac{1}{(b + 1)q_k}.$$

If $b^2 + 2b \leq a_{k+1} \leq b^2 + 3b$, then $\lfloor \sqrt{4a_{k+1} + 5} \rfloor = 2b + 2$ and

$$(2b - 1) \|q_k \theta\| + \|q_{k+1} \theta\| < (b - 1) \|q_k \theta\| + \frac{1}{(b + 1)q_k}.$$

Finally if $a_{k+1} = b^2 + 3b + 1$ we have $\lfloor \sqrt{4a_{k+1} + 5} \rfloor = 2b + 3$ and

$$2b \|q_k \theta\| + \|q_{k+1} \theta\| < (b - 1) \|q_k \theta\| + \frac{1}{(b + 1)q_k}.$$

Therefore, in all cases, we have

$$\left(\lfloor \sqrt{4a_{k+1} + 5} \rfloor - 3 \right) \|q_k \theta\| + \|q_{k+1} \theta\| \leq (b - 1) \|q_k \theta\| + \frac{1}{(b + 1)q_k}.$$

By Lemma 11, we have

$$\bigcup_{1 \leq i \leq q_k} (i\theta - \|q_k \theta\|, i\theta + r_{k+1} \|q_k \theta\| + \|q_{k+1} \theta\|) \subset F_k.$$

Now we prove the second assertion of the lemma. We assume that $a_{k+1} = 4$ and $a_{k+2} \geq 2$, since other cases are implied by the first assertion by the definition of \tilde{r}_{k+1} . We will apply Lemma 7 (i). To this end, we will obtain in the following many estimates of the form:

$$(b - 1) \|q_k \theta\| + \frac{1}{bq_k + i} \quad (1 \leq i \leq q_k).$$

(a) If $a_k = 1$, then we have

$$\begin{aligned} q_k \|q_{k+1} \theta\| &= q_{k-1} \|q_{k+1} \theta\| + q_{k-2} \|q_{k+1} \theta\| \\ &\leq (a_{k+2} - 1) q_{k-1} \|q_{k+1} \theta\| + q_{k-2} \|q_{k+1} \theta\| \\ &< a_{k+2} q_{k-1} \|q_{k+1} \theta\| < q_{k-1} \|q_k \theta\|. \end{aligned}$$

Hence, for all $b \geq 1$

$$\begin{aligned} (b + 1)q_k (\|q_k \theta\| + \|q_{k+1} \theta\|) &\leq 4q_k \|q_k \theta\| + 2q_k \|q_{k+1} \theta\| \\ &< 4q_k \|q_k \theta\| + q_{k-1} \|q_k \theta\| + q_k \|q_{k+1} \theta\| \\ &= q_{k+1} \|q_k \theta\| + q_k \|q_{k+1} \theta\| = 1, \end{aligned}$$

which yields that for all $b \geq 1$

$$2 \|q_k \theta\| + \|q_{k+1} \theta\| < (b - 1) \|q_k \theta\| + \frac{1}{(b + 1)q_k}.$$

Therefore, by Lemma 7 (i), we have

$$\bigcup_{1 \leq i \leq q_k} (i\theta - \|q_k \theta\|, i\theta + 2 \|q_k \theta\| + \|q_{k+1} \theta\|) \subset F_k.$$

(b) Suppose $a_k \geq 2$. For $1 \leq b \leq 2$, by (25), we have

$$\begin{aligned}
& (bq_k + (\tilde{r}_k + 1)q_{k-1}) ((3-b)\|q_k\theta\| + \|q_{k+1}\theta\|) \\
& \leq \left(bq_k + \left(\frac{a_k}{2} + 1\right)q_{k-1}\right) ((3-b)\|q_k\theta\| + \|q_{k+1}\theta\|) \\
& = (3b - b^2)q_k\|q_k\theta\| + (b-1)q_k\|q_{k+1}\theta\| + \left(\frac{(3-b)a_k}{2} + 2 - b\right)q_{k-1}\|q_k\theta\| \\
& \quad + \left(\frac{a_k}{2} + 1\right)q_{k-1}\|q_{k+1}\theta\| + q_k\|q_{k+1}\theta\| + q_{k-1}\|q_k\theta\|.
\end{aligned}$$

By (2) and (1) respectively, we have the estimations:

$$\|q_{k+1}\theta\| \leq \frac{1}{a_{k+2}}\|q_k\theta\| \quad \text{and} \quad q_{k-1} < \frac{q_k}{a_k}.$$

Thus,

$$\begin{aligned}
& (bq_k + (\tilde{r}_k + 1)q_{k-1}) ((3-b)\|q_k\theta\| + \|q_{k+1}\theta\|) \\
& < \left(3b - b^2 + \frac{b-1}{a_{k+2}} + \frac{3-b}{2} + \frac{2-b}{a_k} + \left(\frac{1}{2} + \frac{1}{a_k}\right)\frac{1}{a_{k+1}}\right)q_k\|q_k\theta\|.
\end{aligned}$$

By using the assumption $a_{k+2} \geq 2$ and $1 \leq b \leq 2$, we then deduce

$$\begin{aligned}
& (bq_k + (\tilde{r}_k + 1)q_{k-1}) ((3-b)\|q_k\theta\| + \|q_{k+1}\theta\|) \\
& \leq \left(3b - b^2 + \frac{b-1}{2} + \frac{3-b}{2} + \frac{2-b}{2} + \frac{1}{2}\right)q_k\|q_k\theta\| + q_k\|q_{k+1}\theta\| + q_{k-1}\|q_k\theta\| \\
& = \left(\frac{5}{2} + \frac{5b}{2} - b^2\right)q_k\|q_k\theta\| + q_k\|q_{k+1}\theta\| + q_{k-1}\|q_k\theta\| \\
& \leq 4q_k\|q_k\theta\| + q_{k-1}\|q_k\theta\| + q_k\|q_{k+1}\theta\| = 1.
\end{aligned}$$

For the last equality, we have used the assumption $a_{k+1} = 4$ and the fact (3).

For $b \geq 3$, it is easy to see that

$$\begin{aligned}
& (bq_k + (\tilde{r}_k + 1)q_{k-1}) ((3-b)\|q_k\theta\| + \|q_{k+1}\theta\|) \\
& \leq 4q_k\|q_k\theta\| + q_{k-1}\|q_k\theta\| + q_k\|q_{k+1}\theta\| = 1.
\end{aligned}$$

Thus, for each $1 \leq i \leq (\tilde{r}_k + 1)q_{k-1}$, we have for any $b \geq 1$

$$2\|q_k\theta\| + \|q_{k+1}\theta\| < (b-1)\|q_k\theta\| + \frac{1}{bq_k + (\tilde{r}_k + 1)q_{k-1}} \leq (b-1)\|q_k\theta\| + \frac{1}{bq_k + i}.$$

By Lemma 7 (i), we have

$$\bigcup_{i=1}^{(\tilde{r}_k + 1)q_{k-1}} (i\theta - \|q_k\theta\|, i\theta + \tilde{r}_{k+1}\|q_k\theta\| + \|q_{k+1}\theta\|) \subset F_k. \quad \square$$

If $a_{k+1} = 2$, then $\tilde{r}_{k+1} = 1$ and

$$\begin{aligned} & \bigcup_{i=1}^{q_k} (i\theta - \|q_k\theta\|, i\theta + \|q_k\theta\| + \|q_{k+1}\theta\|) \\ & \supset \bigcup_{i=1}^{q_{k-1}} \bigcup_{c=0}^{a_k-1} ((i + cq_{k-1})\theta - \|q_k\theta\|, (i + cq_{k-1})\theta + \|q_k\theta\| + \|q_{k+1}\theta\|) \\ & = \bigcup_{i=1}^{q_{k-1}} (i\theta - (a_k - 1)\|q_{k-1}\theta\| - \|q_k\theta\|, i\theta + \|q_k\theta\| + \|q_{k+1}\theta\|). \end{aligned}$$

Denote

$$\tilde{F}_k = \begin{cases} \mathbb{T}, & a_{k+1} = 1, \\ \bigcup_{i=1}^{q_{k-1}} (i\theta - (a_k - 1)\|q_{k-1}\theta\| - \|q_k\theta\|, i\theta + \|q_k\theta\| + \|q_{k+1}\theta\|), & a_{k+1} = 2, \\ \bigcup_{i=1}^{q_k} (i\theta - \|q_k\theta\|, i\theta + \tilde{r}_{k+1}\|q_k\theta\| + \|q_{k+1}\theta\|), & a_{k+1} \geq 3 \end{cases} \quad (29)$$

for even k . Note that for odd k , we have the symmetric formula. By Lemma 12 we have $\tilde{F}_k \subset F_k$, thus

$$\cap \tilde{F}_k \subset \cap F_k.$$

Now we will investigate the numbers of subintervals. Let (u_j) be the Fibonacci sequence defined by $u_0 = 0, u_1 = 1$ and $u_{j+1} = u_j + u_{j-1}$. We have the following lemma.

Lemma 13. *If $a_{k+j} = 1, 2 \leq j \leq \ell$, then for each $1 \leq i \leq q_k$*

$$\#\{1 \leq j \leq q_{k+\ell} : j\theta \in (i\theta - \|q_k\theta\|, i\theta + \tilde{r}_{k+1}\|q_k\theta\| + \|q_{k+1}\theta\|)\} \geq u_\ell \tilde{r}_{k+1} + u_{\ell+1}$$

and if $a_{k+2} = 2$ and $a_{k+j} = 1, 3 \leq j \leq \ell$, then for each $1 \leq i \leq q_k$

$$\begin{aligned} \#\{1 \leq j \leq q_{k+\ell} : j\theta \in (i\theta - \|q_{k+1}\theta\| - \|q_{k+2}\theta\|, i\theta + \tilde{r}_{k+1}\|q_k\theta\| + \|q_{k+1}\theta\|)\} \\ \geq u_{\ell+1}(\tilde{r}_{k+1} + 1). \end{aligned}$$

Proof. For each positive integer n we have a unique representation (called Ostrowski's expansion, see [34]):

$$n = \sum_{j=0}^{\infty} c_{j+1} q_j,$$

where $0 \leq c_1 < a_1, 0 \leq c_{j+1} \leq a_{j+1}$, and $c_j = 0$ if $c_{j+1} = a_{j+1}$.

If

$$n = \sum_{j=k}^{k+\ell-1} c_{j+1} q_j$$

is an integer with its representation coefficients:

$$0 \leq c_{k+1} \leq \tilde{r}_{k+1} < a_{k+1}, \quad 0 \leq c_{j+1} \leq a_{j+1} = 1 \quad (k < j \leq k + \ell), \quad (30)$$

then, by the fact that $q_k\theta - p_k > 0$ if and only if k is even, we have

$$\begin{aligned} n\theta &= c_{k+1}q_k\theta + c_{k+2}q_{k+1}\theta + \cdots + c_{k+\ell}q_{k+\ell-1}\theta \\ &\leq \tilde{r}_{k+1}q_k\theta + a_{k+3}q_{k+2}\theta + a_{k+5}q_{k+4}\theta + \cdots < \tilde{r}_{k+1}\|q_k\theta\| + \|q_{k+1}\theta\|, \\ n\theta &\geq a_{k+2}q_{k+1}\theta + a_{k+4}q_{k+3}\theta + \cdots > -\|q_k\theta\|, \end{aligned}$$

thus, we have

$$i\theta - \|q_k\theta\| < (i+n)\theta < i\theta + \tilde{r}_{k+1}\|q_k\theta\| + \|q_{k-1}\theta\|.$$

The number of the above integer n 's of which expansion satisfying (30) is the number of ℓ -tuples of $(c_{k+1}, c_{k+2}, \dots, c_{k+\ell})$ such that

$$0 \leq c_{k+1} \leq \tilde{r}_{k+1} < a_{k+1}, 0 \leq c_{j+1} \leq 1 = a_{j+1} \quad \text{for } k+1 \leq j \leq k+\ell-1$$

and

$$c_j c_{j+1} = 0 \quad \text{for } k+2 \leq j \leq k+\ell-1,$$

which thus is $u_\ell \tilde{r}_{k+1} + u_{\ell+1}$. Hence the first part of the lemma holds.

Similarly, if

$$n = \sum_{j=k}^{k+\ell-1} c_{j+1} q_j$$

satisfies that for $k+2 \leq j \leq k+\ell-1$

$$0 \leq c_{k+1} \leq \tilde{r}_{k+1} < a_{k+1}, \quad 0 \leq c_{k+2} \leq 1 < a_{k+2}, \quad 0 \leq c_{j+1} \leq 1 = a_{j+1}$$

and

$$c_j c_{j+1} = 0 \quad \text{for } k+3 \leq j \leq k+\ell-1,$$

then

$$i\theta - \|q_{k+1}\theta\| - \|q_{k+2}\theta\| < (i+n)\theta < i\theta + \tilde{r}_{k+1}\|q_k\theta\| + \|q_{k+1}\theta\|$$

and the number of such integer n 's is $u_{\ell+1}(\tilde{r}_{k+1} + 1)$. Thus we have the second part of the lemma. \square

To see clearly the Cantor structure, we sometimes need to unify two consecutive levels of the intervals as one level. Let

$$D_k := \begin{cases} \tilde{F}_k, & \text{if } a_{k+1} \neq 2, a_{k+2} \neq 2, \\ \tilde{F}_k \cap \tilde{F}_{k+1}, & \text{if } a_{k+1} \neq 2, a_{k+2} = 2, \\ \tilde{F}_{k+1}, & \text{if } a_{k+1} = 2, a_{k+2} = 2, \\ \mathbb{T}, & \text{if } a_{k+1} = 2, a_{k+2} \neq 2 \end{cases} \quad (31)$$

and

$$\Lambda := \{k \in \mathbb{N} : a_{k+1} \geq 3 \text{ or } a_{k+2} = 2\}.$$

Then D_k consists of q_k intervals if $k \in \Lambda$ and $D_k = \mathbb{T}$ if $k \notin \Lambda$. Note that for all $\ell \geq 1$

$$\bigcap_{k=\ell}^{\infty} D_k \subset \bigcap_{k=\ell+1}^{\infty} \tilde{F}_k.$$

Thus, we need only to give a lower bound of the Hausdorff dimension of $\bigcap_{k=\ell}^{\infty} D_k$. To this end, we will use later a subsequence of D_k as basic intervals for construction of a Cantor set.

By (29), if $a_{k+1} = 1$, $a_{k+2} = 2$, then $\tilde{r}_{k+1} = 0$ and

$$\begin{aligned} D_k &= \tilde{F}_k \cap \tilde{F}_{k+1} = \mathbb{T} \cap \tilde{F}_{k+1} = \tilde{F}_{k+1} \\ &= \bigcup_{i=1}^{q_k} (i\theta - \|q_{k+1}\theta\| - \|q_{k+2}\theta\|, i\theta + (a_{k+1} - 1)\|q_k\theta\| + \|q_{k+1}\theta\|) \\ &= \bigcup_{i=1}^{q_k} (i\theta - \|q_{k+1}\theta\| - \|q_{k+2}\theta\|, i\theta + \tilde{r}_{k+1}\|q_k\theta\| + \|q_{k+1}\theta\|). \end{aligned}$$

If $a_{k+1} = 2$, $a_{k+2} = 2$, then $\tilde{r}_{k+1} = 1$ and

$$\begin{aligned} D_k &= \tilde{F}_{k+1} = \bigcup_{i=1}^{q_k} (i\theta - \|q_{k+1}\theta\| - \|q_{k+2}\theta\|, i\theta + (a_{k+1} - 1)\|q_k\theta\| + \|q_{k+1}\theta\|) \\ &= \bigcup_{i=1}^{q_k} (i\theta - \|q_{k+1}\theta\| - \|q_{k+2}\theta\|, i\theta + \tilde{r}_{k+1}\|q_k\theta\| + \|q_{k+1}\theta\|). \end{aligned}$$

If $a_{k+1} \geq 3$, $a_{k+2} = 2$, then $\tilde{r}_{k+1} = 1$ and

$$\begin{aligned} D_k &= \tilde{F}_k \cap \tilde{F}_{k+1} \\ &= \bigcup_{i=1}^{q_k} (i\theta - \|q_k\theta\|, i\theta + \tilde{r}_{k+1}\|q_k\theta\| + \|q_{k+1}\theta\|) \\ &\quad \cap \bigcup_{i=1}^{q_k} (i\theta - \|q_{k+1}\theta\| - \|q_{k+2}\theta\|, i\theta + (a_{k+1} - 1)\|q_k\theta\| + \|q_{k+1}\theta\|) \\ &= \bigcup_{i=1}^{q_k} (i\theta - \|q_{k+1}\theta\| - \|q_{k+2}\theta\|, i\theta + \tilde{r}_{k+1}\|q_k\theta\| + \|q_{k+1}\theta\|). \end{aligned}$$

Therefore, for $k \in \Lambda$, we have

$$D_k = \begin{cases} \bigcup_{i=1}^{q_k} (i\theta - \|q_k\theta\|, i\theta + \tilde{r}_{k+1}\|q_k\theta\| + \|q_{k+1}\theta\|), & \text{if } a_{k+2} \neq 2, \\ \bigcup_{i=1}^{q_k} (i\theta - \|q_{k+1}\theta\| - \|q_{k+2}\theta\|, i\theta + \tilde{r}_{k+1}\|q_k\theta\| + \|q_{k+1}\theta\|), & \text{if } a_{k+2} = 2. \end{cases}$$

Let $m_{k,k+\ell}$ denote the number of intervals of $D_{k+\ell}$ contained in each interval of D_k .

Lemma 14. *If $k, k + \ell \in \Lambda$ and $j \notin \Lambda$ for $k < j < k + \ell$, then*

$$m_{k,k+\ell} \geq \begin{cases} \frac{q_{k+\ell}}{q_k} \sqrt{\frac{q_k}{q_{k+1}}}, & \text{if } a_j = 1 \text{ for } k+2 \leq j \leq k+\ell, \\ \frac{q_{k+\ell}}{q_k} \sqrt{\frac{q_k}{q_{k+2}}}, & \text{if } a_{k+2} = 2, \text{ and } a_j = 1 \text{ for } k+2 < j \leq k+\ell. \end{cases}$$

Furthermore, the above lower estimate can be written as

$$m_{k,k+\ell} \geq \prod_{k \leq j < \ell} \sqrt{\frac{q_{j+1}}{q_j}} \cdot \prod_{\substack{k \leq j < \ell \\ a_{j+1}=1}} \sqrt{\frac{q_{j+1}}{q_j}}.$$

Proof. By Lemma 13, the number of intervals is

$$m_{k,k+\ell} \geq \begin{cases} u_\ell \tilde{r}_{k+1} + u_{\ell+1}, & \text{if } a_{k+2} \neq 2, \\ u_{\ell+1}(\tilde{r}_{k+1} + 1), & \text{if } a_{k+2} = 2. \end{cases} \quad (32)$$

If $\ell = 1$, i.e., $a_{k+2} \neq 1$, then by (24),

$$m_{k,k+\ell} = \tilde{r}_{k+1} + 1 \geq \sqrt{\frac{q_{k+1}}{q_k}}.$$

Assume $\ell > 1$. Then $a_{k+2} \leq 2$ and $a_j = 1$ for all $k+2 < j \leq k+\ell$. Thus

$$q_{k+\ell} = u_{\ell-1}q_{k+2} + u_{\ell-2}q_{k+1} = (a_{k+2}u_{\ell-1} + u_{\ell-2})q_{k+1} + u_{\ell-1}q_k.$$

If $a_{k+2} = 1$, then, by (32) and (22), we have

$$\begin{aligned} m_{k,k+\ell} &\geq u_\ell \tilde{r}_{k+1} + u_\ell + u_{\ell-1} > u_\ell \left(\sqrt{\frac{q_{k+1}}{q_k}} - \frac{1}{2} \left(1 - \sqrt{\frac{q_k}{q_{k+1}}} \right) + \frac{u_{\ell-1}}{u_\ell} \right) \\ &\geq u_\ell \left(\sqrt{\frac{q_{k+1}}{q_k}} - \frac{u_{\ell-1}}{u_\ell} \left(1 - \sqrt{\frac{q_k}{q_{k+1}}} \right) + \frac{u_{\ell-1}}{u_\ell} \right) \\ &= u_\ell \left(\sqrt{\frac{q_{k+1}}{q_k}} + \frac{u_{\ell-1}}{u_\ell} \sqrt{\frac{q_k}{q_{k+1}}} \right) = \frac{u_\ell q_{k+1} + u_{\ell-1} q_k}{q_k} \sqrt{\frac{q_k}{q_{k+1}}} = \frac{q_{k+\ell}}{q_k} \sqrt{\frac{q_k}{q_{k+1}}}. \end{aligned}$$

If $a_{k+2} = 2$, then, by (32) and (23), we have

$$\begin{aligned} m_{k,k+\ell} &\geq u_{\ell+1} \tilde{r}_{k+1} + u_{\ell+1} \\ &> \frac{u_{\ell+1}}{\sqrt{2}} \left(\sqrt{\frac{q_{k+1}}{q_k}} + \frac{1}{2} \sqrt{\frac{q_k}{q_{k+1}}} \right) \geq \frac{u_{\ell+1}}{\sqrt{2}} \sqrt{\frac{q_{k+1}}{q_k}} + \frac{u_{\ell-1}}{\sqrt{2}} \sqrt{\frac{q_k}{q_{k+1}}} \\ &= \frac{u_{\ell+1} q_{k+1} + u_{\ell-1} q_k}{q_k} \sqrt{\frac{q_k}{2q_{k+1}}} = \frac{q_{k+\ell}}{q_k} \sqrt{\frac{q_k}{2q_{k+1}}} > \frac{q_{k+\ell}}{q_k} \sqrt{\frac{q_k}{q_{k+2}}}. \end{aligned}$$

The last assertion is followed by a direct calculation. \square

Next, we will investigate the gaps between two intervals at the same level.

Lemma 15. *Let ϵ_k be the gap between two intervals in D_k . Then*

$$\epsilon_k \geq \frac{1}{7} \|q_{k-1}\theta\|.$$

Proof. Let $k \in \Lambda$. If $a_{k+1} \geq 3$ then

$$\epsilon_k \geq (a_{k+1} - 1 - \tilde{r}_{k+1}) \|q_k\theta\|.$$

It can be easily checked that $\tilde{r}_{k+1} + 1 \leq \frac{1}{5}(4a_{k+1} - 1)$ for $a_{k+1} \geq 3$. Since $\|q_{k-1}\theta\| = a_{k+1}\|q_k\theta\| + \|q_{k+1}\theta\| < (a_{k+1} + 1)\|q_k\theta\|$, we have

$$\epsilon_k > \frac{a_{k+1} - 1 - \tilde{r}_{k+1}}{a_{k+1} + 1} \|q_{k-1}\theta\| \geq \frac{1}{5} \|q_{k-1}\theta\|.$$

If $a_{k+1} \leq 2$ and $a_{k+2} = 2$, then

$$\|q_{k-1}\theta\| \leq 2\|q_k\theta\| + \|q_{k+1}\theta\| = 5\|q_{k+1}\theta\| + 2\|q_{k+2}\theta\| < 7\|q_{k+1}\theta\|.$$

Thus,

$$\begin{aligned} \epsilon_k &= \|q_{k-1}\theta\| - (\tilde{r}_{k+1}\|q_k\theta\| + 2\|q_{k+1}\theta\| + \|q_{k+2}\theta\|) \\ &= (a_{k+1} - \tilde{r}_{k+1})\|q_k\theta\| - \|q_{k+1}\theta\| - \|q_{k+2}\theta\| \\ &= \|q_k\theta\| - \|q_{k+1}\theta\| - \|q_{k+2}\theta\| \\ &= \|q_{k+1}\theta\| > \frac{1}{7} \|q_{k-1}\theta\|. \end{aligned} \quad \square$$

Now we are ready to estimate the Hausdorff dimension of $\mathcal{U}_1[\theta]$.

Theorem 16. *For $\tau = 1$ and for any irrational θ*

$$\dim_H(\mathcal{U}_\tau[\theta]) \geq \frac{1}{w(\theta) + 1}.$$

Proof. Let $\{k_i\}_{i=1}^\infty$ be the increasing sequence of $\Lambda = \{k_i : i \in \mathbb{N}\}$. Denote by $m_i = m_{k_{i-1}, k_i}$, the number of intervals of D_{k_i} in an interval of $D_{k_{i-1}}$. Then, by

Fact 9, Lemmas 14 and 15, we have

$$\begin{aligned}
\dim_H(\mathcal{U}_\tau[\theta]) &\geq \dim_H\left(\bigcap_{i=1}^{\infty} D_{k_i}\right) \geq \liminf_i \frac{\log(m_1 \cdots m_i)}{-\log(m_{i+1}\varepsilon_{k_{i+1}})} \\
&\quad \frac{1}{2} \sum_{0 \leq k < k_i} \log \frac{q_{k+1}}{q_k} + \frac{1}{2} \sum_{\substack{0 \leq k < k_i \\ a_{k+1}=1}} \log \frac{q_{k+1}}{q_k} \\
&\geq \liminf_i \frac{\frac{1}{2} \sum_{0 \leq k < k_i} \log \frac{q_{k+1}}{q_k} + \frac{1}{2} \sum_{\substack{0 \leq k < k_i \\ a_{k+1}=1}} \log \frac{q_{k+1}}{q_k} - \log \frac{\|q_{k_{i+1}-1}\theta\|}{7}}{-\frac{1}{2} \sum_{k_i \leq k < k_{i+1}} \log \frac{q_{k+1}}{q_k} - \frac{1}{2} \sum_{\substack{k_i \leq k < k_{i+1} \\ a_{k+1}=1}} \log \frac{q_{k+1}}{q_k} - \log \frac{\|q_{k_{i+1}-1}\theta\|}{7}}{\log q_{k_i} + \sum_{\substack{1 \leq k < k_i \\ a_{k+1}=1}} \log \frac{q_{k+1}}{q_k}} \\
&= \liminf_i \frac{\log q_{k_i} + \sum_{\substack{1 \leq k < k_i \\ a_{k+1}=1}} \log \frac{q_{k+1}}{q_k}}{\log q_{k_i} + \log q_{k_{i+1}} - \sum_{\substack{k_i \leq k < k_{i+1} \\ a_{k+1}=1}} \log \frac{q_{k+1}}{q_k}} \\
&\geq \liminf_i \frac{\log q_{k_i}}{\log q_{k_i} + \log q_{k_i+t(i)}} = \frac{1}{w+1},
\end{aligned} \tag{33}$$

where $t(i) = 1$ if $k_i + 1 = k_{i+1}$ or $a_{k_i+2} = 1$ and $t(i) = 2$ if $a_{k_i+2} = 2$. \square

Proof of Theorem 2. When $\tau < 1$ or $\tau > 1$, the proof is the same as that of Theorem 1. The case of $\tau = 1$ follows from Theorem 16. \square

5. PROOFS OF THEOREMS 3 AND 5

Using Theorem 16, we can prove Theorem 3.

Proof of Theorem 3. Let us use the same notation $(q_{k_j})_{j \geq 1}$ for the subsequences selected in Theorem 1 for the two cases $1/w(\theta) < \tau < 1$ and $1 < \tau < w(\theta)$. Then by the fact that $n_j = q_{k_j}$ increases super-exponentially, we can replace $\|n_j\theta\|$ by $q_{k_{j+1}}^{-1}$ and rewrite the formula in Theorem 1 as follows.

$$\dim_H(\mathcal{U}_\tau[\theta]) = \begin{cases} \liminf_{i \rightarrow \infty} \frac{\log\left(\prod_{j=1}^{i-1} (q_{k_j}^{1/\tau} q_{k_{j+1}}^{-1}) \cdot q_{k_i}^{1/\tau+1}\right)}{\log(q_{k_i} q_{k_{i+1}})}, & \text{if } \frac{1}{w(\theta)} < \tau < 1, \\ \liminf_{k \rightarrow \infty} \frac{-\log\left(\prod_{j=1}^{i-1} q_{k_j} q_{k_{j+1}}^{-1/\tau}\right)}{\log(q_{k_i} q_{k_{i+1}})}, & \text{if } 1 < \tau < w(\theta). \end{cases}$$

Further, let w_j be the real numbers defined by $2q_{k_{j+1}} = q_{k_j}^{w_j}$ for the case $1/w(\theta) < \tau < 1$ and $2^{w(\theta)+1}q_{k_{j+1}} = q_{k_j}^{w_j}$ for the case $1 < \tau < w(\theta)$. Then by (4), $w_j \geq 1/\tau$ if $1/w(\theta) < \tau < 1$ and $w_j \geq \tau$ if $1 < \tau < w(\theta)$. By (5), we have

$$\overline{\lim}_{j \rightarrow \infty} w_j = w(\theta), \tag{34}$$

and the dimension $\dim_H(\mathcal{U}_\tau[\theta])$ is equal to

$$\begin{cases} \varliminf_{i \rightarrow \infty} \left(\frac{1/\tau + 1}{w_i + 1} - \sum_{j=1}^{i-1} \frac{w_j - 1/\tau}{w_i + 1} \cdot \frac{\log q_{k_j}}{\log q_{k_i}} \right), & \text{if } \frac{1}{w(\theta)} < \tau < 1, \\ \varliminf_{i \rightarrow \infty} \sum_{j=1}^{i-1} \frac{w_j/\tau - 1}{w_i + 1} \cdot \frac{\log q_{k_j}}{\log q_{k_i}}, & \text{if } 1 < \tau < w(\theta). \end{cases} \quad (35)$$

Now fix $w(\theta) = w \in (1, +\infty]$. We have

$$0 < \frac{\log q_{k_j}}{\log q_{k_i}} = \frac{\log q_{k_j}}{\log q_{k_{j+1}}} \cdots \frac{\log q_{k_{i-1}}}{\log q_{k_i}} \leq \frac{\log q_{k_j}}{\log q_{k_{j+1}}} \cdots \frac{\log q_{k_{i-1}}}{\log q_{k_{i-1}+1}} = \frac{1}{w_j \cdots w_{i-1}}.$$

Hence, if $\frac{1}{w(\theta)} < \tau < 1$,

$$0 \leq (w_j - 1/\tau) \cdot \frac{\log q_{k_j}}{\log q_{k_i}} \leq \frac{1}{w_{j+1} \cdots w_{i-1}} - \frac{1}{\tau w_j \cdots w_{i-1}},$$

and if $1 < \tau < w(\theta)$,

$$0 \leq (w_j/\tau - 1) \cdot \frac{\log q_{k_j}}{\log q_{k_i}} \leq \frac{1}{\tau w_{j+1} \cdots w_{i-1}} - \frac{1}{w_j \cdots w_{i-1}}.$$

Let

$$S_{i-1} = \frac{1}{w_1 \cdots w_{i-1}} + \frac{1}{w_2 \cdots w_{i-1}} + \cdots + \frac{1}{w_{i-1}}.$$

Then for $1/w < \tau < 1$

$$\varliminf_{i \rightarrow \infty} \frac{1}{w_i + 1} \left(\frac{1}{\tau} + \left(\frac{1}{\tau} - 1 \right) S_{i-1} + \frac{1}{w_1 \cdots w_{i-1}} \right) \leq \dim_H(\mathcal{U}_\tau[\theta]) \leq \varliminf_{i \rightarrow \infty} \frac{1/\tau + 1}{w_i + 1}$$

and for $1 < \tau < w$

$$0 \leq \dim_H(\mathcal{U}_\tau[\theta]) \leq \varliminf_{i \rightarrow \infty} \frac{1}{w_i + 1} \left(\frac{1}{\tau} - \left(1 - \frac{1}{\tau} \right) S_{i-1} - \frac{1}{\tau w_1 \cdots w_{i-1}} \right).$$

If $w = \infty$, then $\overline{\lim} w_i = \infty$ for both two cases $0 = 1/w(\theta) < \tau < 1$ and $1 < \tau < w(\theta) = \infty$. Thus by (35), we have

$$\dim_H(\mathcal{U}_\tau[\theta]) \leq \begin{cases} \varliminf_{i \rightarrow \infty} \frac{1/\tau + 1}{w_i + 1} = 0, & 0 < \tau < 1, \\ \varliminf_{i \rightarrow \infty} \frac{1}{w_i + 1} \cdot \frac{1}{\tau} = 0, & 1 < \tau < \infty. \end{cases}$$

Therefore, $\dim_H(\mathcal{U}_\tau[\theta]) = 0$ for all $\tau > 0$.

If $w < \infty$, then by (34), for any $\varepsilon > 0$ there is N such that if $i > N$ then

$$S_{i-1} = \frac{1}{w_1 \cdots w_{i-1}} + \cdots + \frac{1}{w_{i-1}} > \frac{1}{(w + \varepsilon)^{i-N}} + \cdots + \frac{1}{w + \varepsilon} = \frac{1 - (w + \varepsilon)^{-i+N}}{w + \varepsilon - 1}.$$

Thus, for $1/w < \tau < 1$

$$\frac{1}{w + 1} \left(\frac{1}{\tau} + \frac{1/\tau - 1}{w - 1} \right) \leq \dim_H(\mathcal{U}_\tau[\theta]) \leq \frac{1/\tau + 1}{w + 1},$$

and for $1 < \tau < w$

$$0 \leq \dim_H(\mathcal{U}_\tau[\theta]) \leq \frac{1}{w+1} \left(\frac{1/\tau - 1}{w-1} + \frac{1}{\tau} \right).$$

For the case of $\tau = 1$, we complete the proof by Theorem 16. \square

Now we are ready to prove Theorem 5.

Proof of Theorem 5. Let $1/w < \tau' < \tau < 1$ and (k_i) and (k'_i) be the maximal sequences of

$$q_{k_i} \|q_{k_i} \theta\|^\tau < 1, \quad q_{k'_i} \|q_{k'_i} \theta\|^{\tau'} < 1.$$

Note that (k'_i) is a subsequence of (k_i) .

Let w_j, w'_j be the real numbers defined by $2q_{k_j+1} = q_{k_j}^{w_j}$, $2q_{k'_j+1} = q_{k'_j}^{w'_j}$ as in the proof of Theorem 3. Recall that for all j , we have $w_j \tau \geq 1$ and $w'_j \tau' \geq 1$. Thus, by noting the fact $q_{k_{j+1}} \geq q_{k_j+1} > q_{k_j}^{1/\tau}$, we have

$$\begin{aligned} & \frac{1/\tau + 1}{w_i + 1} - \sum_{j=1}^{i-1} \frac{w_j - 1/\tau}{w_i + 1} \cdot \frac{\log q_{k_j}}{\log q_{k_i}} \\ &= \frac{1/\tau' + 1}{w_i + 1} - \frac{1/\tau' - 1/\tau}{w_i + 1} - \sum_{j=1}^{i-1} \frac{w_j - 1/\tau'}{w_i + 1} \cdot \frac{\log q_{k_j}}{\log q_{k_i}} - \sum_{j=1}^{i-1} \frac{1/\tau' - 1/\tau}{w_i + 1} \cdot \frac{\log q_{k_j}}{\log q_{k_i}} \\ &\geq \frac{1/\tau' + 1}{w_i + 1} - \sum_{j=1}^{i-1} \frac{w_j - 1/\tau'}{w_i + 1} \cdot \frac{\log q_{k_j}}{\log q_{k_i}} - \sum_{j=1}^i \frac{1/\tau' - 1/\tau}{1/\tau^{i-j}(1/\tau + 1)} \\ &\geq \frac{1/\tau' + 1}{w_i + 1} - \sum_{j=1}^{i-1} \frac{w_j - 1/\tau'}{w_i + 1} \cdot \frac{\log q_{k_j}}{\log q_{k_i}} - \frac{\tau - \tau'}{\tau'(1 - \tau^2)}. \end{aligned} \quad (36)$$

Let s be the index such that $k'_s < k_i < k'_{s+1}$. Noting that $w_j - 1/\tau' < 0$ if k_j is not in the subsequence (k'_i) , we have

$$\frac{1/\tau' + 1}{w_i + 1} - \sum_{j=1}^{i-1} \frac{w_j - 1/\tau'}{w_i + 1} \cdot \frac{\log q_{k_j}}{\log q_{k_i}} \geq \frac{1/\tau' + 1}{w_i + 1} - \sum_{j=1}^s \frac{w'_j - 1/\tau'}{w_i + 1} \cdot \frac{\log q_{k'_j}}{\log q_{k_i}}. \quad (37)$$

By the choice of s , we know $q_{k_i} \geq q_{k'_s+1} = q_{k'_s}^{w'_s}$. Hence, the right hand side of (37) is bigger than

$$\frac{1/\tau' + 1}{w_i + 1} - \frac{w'_s - 1/\tau'}{(w_i + 1)w'_s} - \sum_{j=1}^{s-1} \frac{w'_j - 1/\tau'}{w_i + 1} \cdot \frac{\log q_{k'_j}}{w'_s \log q_{k'_s}},$$

which is equal to

$$\frac{1 + 1/w'_s}{\tau'(w_i + 1)} - \sum_{j=1}^{s-1} \frac{w'_j - 1/\tau'}{(w_i + 1)w'_s} \cdot \frac{\log q_{k'_j}}{\log q_{k'_s}}.$$

Reminding the fact $1/\tau < w_i < 1/\tau'$, we then deduce that

$$\frac{1/\tau' + 1}{w_i + 1} - \sum_{j=1}^{i-1} \frac{w_j - 1/\tau'}{w_i + 1} \cdot \frac{\log q_{k_j}}{\log q_{k_i}} \geq \frac{1 + 1/w'_s}{\tau' + 1} - \sum_{j=1}^{s-1} \frac{w'_j - 1/\tau'}{(1/\tau + 1)w'_s} \cdot \frac{\log q_{k'_j}}{\log q_{k'_s}}.$$

By verifying $(1/\tau + 1)w'_s > w'_s + 1$ and

$$\frac{1 + 1/w'_s}{\tau' + 1} \geq \frac{1/\tau' + 1}{w'_s + 1},$$

we obtain

$$\frac{1/\tau' + 1}{w_i + 1} - \sum_{j=1}^{i-1} \frac{w_j - 1/\tau'}{w_i + 1} \cdot \frac{\log q_{k_j}}{\log q_{k_i}} \geq \frac{1/\tau' + 1}{w'_s + 1} - \sum_{j=1}^{s-1} \frac{w'_j - 1/\tau'}{w'_s + 1} \cdot \frac{\log q_{k'_j}}{\log q_{k'_s}}. \quad (38)$$

Therefore, combining (36) and (38), we have for $k'_s \leq k_i < k'_{s+1}$,

$$\frac{1/\tau + 1}{w_i + 1} - \sum_{j=1}^{i-1} \frac{w_j - 1/\tau}{w_i + 1} \cdot \frac{\log q_{k_j}}{\log q_{k_i}} \geq \frac{1/\tau' + 1}{w'_s + 1} - \sum_{j=1}^{s-1} \frac{w'_j - 1/\tau'}{w'_s + 1} \cdot \frac{\log q_{k'_j}}{\log q_{k'_s}} - \frac{\tau - \tau'}{\tau'(1 - \tau^2)}.$$

Hence, by (35), we have

$$\begin{aligned} \dim_H(\mathcal{U}_\tau[\theta]) &= \varliminf_{i \rightarrow \infty} \left(\frac{1/\tau + 1}{w_i + 1} - \sum_{j=1}^{i-1} \frac{w_j - 1/\tau}{w_i + 1} \cdot \frac{\log q_{k_j}}{\log q_{k_i}} \right) \\ &\geq \varliminf_{s \rightarrow \infty} \left(\frac{1/\tau' + 1}{w'_s + 1} - \sum_{j=1}^{s-1} \frac{w'_j - 1/\tau'}{w'_s + 1} \cdot \frac{\log q_{k'_j}}{\log q_{k'_s}} \right) - \frac{\tau - \tau'}{\tau'(1 - \tau^2)} \\ &= \dim_H(\mathcal{U}_{\tau'}[\theta]) - \frac{\tau - \tau'}{\tau'(1 - \tau^2)}. \end{aligned}$$

Let $1 < \tau < \tau' < w$. Let (k_i) and (k'_i) be the sequence of

$$q_{k_i}^\tau \|q_{k_i} \theta\| < 2, \quad q_{k'_i}^{\tau'} \|q_{k'_i} \theta\| < 2.$$

Clearly, (k'_i) is a subsequence of (k_i) .

Let w_i be the real numbers defined by $2^{w+1}q_{k_i+1} = q_{k_i}^{w_i}$ as in the proof of Theorem 3. Recall that for all j , we have $w_j \geq \tau$. Then, by (35), we have

$$\begin{aligned} \dim_H(\mathcal{U}_\tau[\theta]) &= \liminf_{i \rightarrow \infty} \sum_{j=1}^{i-1} \frac{w_j/\tau - 1}{w_i + 1} \cdot \frac{\log q_{k_j}}{\log q_{k_i}} \\ &= \liminf_{i \rightarrow \infty} \left(\sum_{j=1}^{i-1} \frac{w_j/\tau' - 1}{w_i + 1} \cdot \frac{\log q_{k_j}}{\log q_{k_i}} + \sum_{j=1}^{i-1} \frac{w_j(\tau' - \tau)}{\tau\tau'(w_i + 1)} \cdot \frac{\log q_{k_j}}{\log q_{k_i}} \right) \\ &\leq \liminf_{i \rightarrow \infty} \left(\sum_{j=1}^{i-1} \frac{w_j/\tau' - 1}{w_i + 1} \cdot \frac{\log q_{k_j}}{\log q_{k_i}} \right) + \liminf_{i \rightarrow \infty} \left(\sum_{j=1}^{i-1} \frac{(\tau' - \tau)w_j}{\tau'(\tau + 1)\tau^{i-j+1}} \right) \\ &\leq \liminf_{i \rightarrow \infty} \left(\sum_{j=1}^{i-1} \frac{w_j/\tau' - 1}{w_i + 1} \cdot \frac{\log q_{k'_j}}{\log q_{k'_i}} \right) + \frac{(\tau' - \tau)w}{\tau\tau'(\tau^2 - 1)}. \end{aligned}$$

Hence,

$$\dim_H(\mathcal{U}_\tau[\theta]) - \dim_H(\mathcal{U}_{\tau'}[\theta]) \leq \frac{(\tau' - \tau)w}{\tau\tau'(\tau^2 - 1)}.$$

Since $\mathcal{U}_\tau[\theta] \supset \mathcal{U}_{\tau'}[\theta]$,

$$\dim_H(\mathcal{U}_\tau[\theta]) - \dim_H(\mathcal{U}_{\tau'}[\theta]) \geq 0.$$

Therefore, the claim holds. \square

6. EXAMPLES

The following examples show that the upper and lower bounds in Theorems 2 and 3 can not be replaced by smaller or larger numbers.

Example 17. Let θ be of irrational exponent $w(\theta) = w > 1$ with $q_{k+1} > q_k^w$ for all k . Then the subsequence k_i in the proof of Theorem 1 is given by $k_i = i$.

Put $q_{k_i+1} = q_{k_i}^{w_i}$. Then $\lim_{i \rightarrow \infty} w_i = w$.

For $1/w < \tau < 1$, we have

$$\begin{aligned} \dim_H(\mathcal{U}_\tau[\theta]) &= \liminf_k \frac{\log(q_1^{1/\tau} \|q_1\theta\| q_2^{1/\tau} \|q_2\theta\| \cdots q_{k-1}^{1/\tau} \|q_{k-1}\theta\| \cdot q_k^{1/\tau+1})}{\log(q_k / \|q_k\theta\|)} \\ &= \liminf_k \frac{\log(q_1^{1/\tau} q_2^{1/\tau-1} \cdots q_{k-1}^{1/\tau-1} \cdot q_k^{1/\tau})}{\log(q_k q_{k+1})} \\ &= \liminf_k \frac{1}{1 + w_{k+1}} \left(\frac{1/\tau}{w_2 \cdots w_k} + \frac{1/\tau - 1}{w_3 \cdots w_k} + \cdots + \frac{1/\tau - 1}{w_k} + \frac{1}{\tau} \right) \\ &= \frac{1}{1 + w} \left(\frac{1/\tau - 1}{w - 1} + \frac{1}{\tau} \right). \end{aligned}$$

For $1 < \tau < w$, we have

$$\begin{aligned}
\dim_H(\mathcal{U}_\tau[\theta]) &= \liminf_k \frac{-\log(q_1 \|q_1 \theta\|^{1/\tau} q_2 \|q_2 \theta\|^{1/\tau} \cdots q_{k-1} \|q_{k-1} \theta\|^{1/\tau})}{\log(q_k / \|q_k \theta\|)} \\
&= - \liminf_k \frac{\log(q_1 q_2^{1-1/\tau} \cdots q_{k-1}^{1-1/\tau} \cdot q_k^{-1/\tau})}{\log(q_k q_{k+1})} \\
&= \liminf_k \frac{1}{1 + w_{k+1}} \left(\frac{1/\tau}{w_2 \cdots w_k} + \frac{1/\tau - 1}{w_3 \cdots w_k} + \cdots + \frac{1/\tau - 1}{w_k} + \frac{1}{\tau} \right) \\
&= \frac{1}{1 + w} \left(\frac{1/\tau - 1}{w - 1} + \frac{1}{\tau} \right).
\end{aligned}$$

Therefore, for each $1/w < \tau < w$ we have

$$\dim_H(\mathcal{U}_\tau[\theta]) = \frac{w/\tau - 1}{w^2 - 1}.$$

Example 18. Assume that θ is an irrational of $w(\theta) = w > 1$ with the subsequence $\{k_i\}$ of $q_{k_i+1} > q_{k_i}^w$ satisfying that $a_{n+1} = 1$ for $n \neq k_i$ and $q_{k_i} > (q_{k_{i-1}+1})^{2^i}$. Then we have

$$\lim_{i \rightarrow \infty} \left(\frac{\log q_{k_1}}{\log q_{k_i}} + \frac{\log q_{k_2}}{\log q_{k_i}} + \cdots + \frac{\log q_{k_{i-1}}}{\log q_{k_i}} \right) = 0.$$

Since w_i converges to w , by (35), the Hausdorff dimension of $\mathcal{U}_\tau[\theta]$ is $\frac{1/\tau+1}{w+1}$ and 0, respectively for $1/w < \tau < 1$ and $\tau > 1$.

If $\tau = 1$, then, by the proof of (33),

$$\begin{aligned}
\dim_H(\mathcal{U}_\tau[\theta]) &\geq \liminf_i \frac{\log q_{k_i} + \sum_{\substack{1 \leq k < k_i \\ a_{k+1}=1}} \log \frac{q_{k+1}}{q_k}}{\log q_{k_i} + \log q_{k_{i+1}} - \sum_{\substack{k_i \leq k < k_{i+1} \\ a_{k+1}=1}} \log \frac{q_{k+1}}{q_k}} \\
&\geq \liminf_i \frac{\log q_{k_i} + (\log q_{k_i} - \log q_{k_{i-1}+1})}{\log q_{k_i} + \log q_{k_{i+1}}} \geq \liminf_i \frac{2 - \log q_{k_{i-1}+1} / \log q_{k_i}}{1 + \log q_{k_{i+1}} / \log q_{k_i}} \\
&\geq \liminf_i \frac{2 - 2^{-i}}{1 + \log q_{k_{i+1}} / \log q_{k_i}} = \frac{2}{w + 1}.
\end{aligned}$$

Hence, we have

$$\dim_H(\mathcal{U}_\tau[\theta]) = \begin{cases} \frac{1/\tau + 1}{w + 1}, & \text{for } 1/w < \tau \leq 1, \\ 0, & \text{for } \tau > 1. \end{cases}$$

Example 19. Let $\theta = \frac{\sqrt{5}-1}{2}$, of which partial quotients $a_k = 1$ for all k . Note that $w(\theta) = 1$. By Lemma 6, $\mathcal{U}_\tau[\theta] = \mathbb{T}$ for $\tau = 1$. Thus, we have

$$\dim_H(\mathcal{U}_\tau[\theta]) = \begin{cases} 1, & \tau \leq 1, \\ 0 & \tau > 1. \end{cases}$$

Example 20. Let θ be the irrational with partial quotient $a_k = k$ for all k . Then $w(\theta) = 1$. Consider the case of $\tau = 1$. By Lemma 7 (iii), we have

$$\begin{aligned} F_k &\subset \bigcup_{i=1}^{q_k} \left(i\theta - 2 \left(\frac{\|q_k\theta\|}{q_k} \right)^{\frac{1}{2}}, i\theta + 2 \left(\frac{\|q_k\theta\|}{q_k} \right)^{\frac{1}{2}} \right) \\ &= \bigcup_{i=1}^{q_k} \left(i\theta - 2 \left(\frac{1}{q_k \|q_k\theta\|} \right)^{\frac{1}{2}} \|q_k\theta\|, i\theta + 2 \left(\frac{1}{q_k \|q_k\theta\|} \right)^{\frac{1}{2}} \|q_k\theta\| \right). \end{aligned}$$

Thus, F_k can be covered by ℓ_k sets of diameter at most δ_k , with

$$\begin{aligned} \ell_k &\leq \left(4 \left(\frac{1}{q_1 \|q_1\theta\|} \right)^{\frac{1}{2}} + 2 \right) \left(4 \left(\frac{1}{q_2 \|q_2\theta\|} \right)^{\frac{1}{2}} + 2 \right) \cdots \left(4 \left(\frac{1}{q_{k-1} \|q_{k-1}\theta\|} \right)^{\frac{1}{2}} + 2 \right) \\ \delta_k &\leq 4 \left(\frac{\|q_k\theta\|}{q_k} \right)^{\frac{1}{2}} < 4 \left(\frac{1}{q_k q_{k+1}} \right)^{\frac{1}{2}}. \end{aligned}$$

Since $x + \frac{1}{2} \leq \frac{3}{2}x$ for $x \geq 1$, we have

$$\ell_k < 6^{k-1} \left(\frac{1}{q_1 \|q_1\theta\|} \cdots \frac{1}{q_{k-1} \|q_{k-1}\theta\|} \right)^{\frac{1}{2}} < 6^{k-1} \left(\frac{2q_2}{q_1} \cdots \frac{2q_k}{q_{k-1}} \right)^{\frac{1}{2}} \leq 12^{k-1} q_k^{\frac{1}{2}}.$$

Thus,

$$\dim_H(\mathcal{U}_\tau[\theta]) \leq \liminf_k \frac{\log \ell_k}{-\log \delta_k} = \liminf_k \frac{(k-1) \log 12 + \frac{1}{2} \log q_k}{-\log 4 + \frac{1}{2}(\log q_k + \log q_{k+1})}.$$

Since

$$\log q_{k+1} \geq \sum_{i=1}^{k+1} \log a_i = \sum_{i=2}^{k+1} \log i \geq (k+1) \log(k+1) - k,$$

one has

$$\lim_{k \rightarrow \infty} \frac{k}{\log q_k} = 0, \quad 1 \leq \lim_{k \rightarrow \infty} \frac{\log q_{k+1}}{\log q_k} \leq \lim_{k \rightarrow \infty} \frac{\log(a_{k+1} + 1) + \log q_k}{\log q_k} = 1$$

Therefore,

$$\dim_H(\mathcal{U}_\tau[\theta]) \leq \liminf_k \frac{\log q_k}{\log q_k + \log q_{k+1}} = \frac{1}{2}.$$

Hence, by Theorem 16, we have

$$\dim_H(\mathcal{U}_\tau[\theta]) = \begin{cases} 1, & \tau < 1, \\ \frac{1}{2}, & \tau = 1, \\ 0 & \tau > 1. \end{cases}$$

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