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Some Limit Theorems for Nonhomogeneous Markov Chains Indexed by an Infinite Tree with Uniformly Bounded Degree[1]

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Abstract : In this paper, a generalized Shannon-McMillan theorem for the nonhomogeneous Markov chains indexed by an infinite tree which has a uniformly bounded degree is discussed by constructing a nonnegative martingale and analytical methods. As corollaries, some Shannon-Mcmillan theorems for the nonhomogeneous Markov chains indexed by a homogeneous tree and the nonhomogeneous Markov chain are obtained. Two results which have been obtained are extended.

Keywords : Shannon-McMillan theorem; Infinite tree; Markov chains; Entropy density; Uniformly bounded degree.
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1 Introduction

A tree is a graph $G = \{T, E\}$ which is connected and contains no circuits. Given any two vertices $\alpha \neq \beta \in T$, let $\overline{\alpha\beta}$ be the unique path connecting α and β. Define the graph distance $d(\alpha, \beta)$ to be the number of edges contained in $\overline{\alpha\beta}$.

In this paper, we mainly consider an infinite tree which has uniformly bounded degree, that is, the numbers of neighbors of any vertices in this tree are uniformly bounded. When the context permit, this type of trees are all denoted simply by

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T. For a better explanation of the tree T, we take Cayley tree $T_{C,N}$ for example. It's a special case of the tree T, the root o of Cayley tree has N neighbors and all the other vertices of it have $N+1$ neighbors each (see Fig. 1).

Let T be an infinite tree with a root o, the set of all vertices with the distance n from the root is called the n-th generation of T, which is denoted by L_n. In other words, L_n represents the set of all vertices on the level n. We denote by $T^{(n)}$ the union of the first n generations of T. Denote by t the t-th vertex from the root to the upper part, from the left side to the right side on the tree. For each vertex t, there is a unique path from o to t, and $|t|$ for the number of the edges on this path. We denote the first predecessor of t by 1_t, the second predecessor of t by 2_t, and denote by n_t the n-th predecessor of t. For any two vertices s and t of the tree T, write $s \leq t$ if s is on the unique path from the root o to t. We denote $s \wedge t$ the vertex nearest from o satisfying $s \wedge t \leq s$ and $s \wedge t \leq t$. $X^A = \{X_t, t \in A\}$ and $|A|$ denote by the number of the vertices of A.

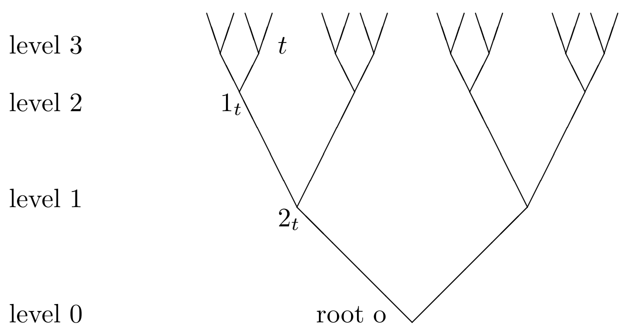

Fig. 1: An infinite tree $T_{C,2}$.

Definition 1.1 (see [1]). Let T be an infinite tree, $S = \{s_0, s_1, s_2, ..., s_{N-1}\}$ a finite state space, $\{X_t, t \in T\}$ be a collection of S-valued random variables defined on the probability space $\{\Omega, \mathcal{F}, \mathcal{P}\}$. Let

$$p = \{p(x), x \in S\} \tag{1.1}$$

be a distribution on S, and

$$P_t = (P_t(y|x)), \quad x, y \in S, \quad t \in T. \tag{1.2}$$

be a series of strictly positive stochastic matrices on S^2. If for any vertex t,

$$\begin{aligned} P(X_t = y | X_{1_t} = x, \text{ and } X_s \text{ for } t \wedge s \leq 1_t) &= P(X_t = y | X_{1_t} = x) \\ &= P_t(y|x) \ \ \forall x, y \in S, \end{aligned} \tag{1.3}$$

and

$$P(X_0 = x) = p(x), \quad \forall x \in S. \tag{1.4}$$

$\{X_t, t \in T\}$ will be called $S-$valued Markov chains indexed by an infinite tree defined as before with the initial distribution (1.1) and transition matrices (1.2).

The above definition is an extension of the definitions of Markov chain fields on trees (see [2]).

Two special finite tree-indexed Markov chains are introduced in Kemeny et al. [1], Spitzer [3], and there the finite transition matrix is assumed to be positive and reversible to its stationary distribution, and this tree-indexed Markov chains ensure that the cylinder probabilities are independent of the direction we travel along a path. In this paper, we have no such assumption.

It is easy to see that when $\{X_t, t \in T\}$ is a T-indexed Markov chain,

$$P\left(x^{T^{(n)}}\right) = P\left(X^{T^{(n)}} = x^{T^{(n)}}\right) = P(X_0 = x_0) \prod_{t \in T^{(n)} \setminus \{o\}} P_t(x_t | x_{1_t}). \tag{1.5}$$

Let T be a tree, $\{X_t, t \in T\}$ be a stochastic process indexed by the tree T with the state space S. Denote

$$P\left(x^{T^{(n)}}\right) = P\left(X^{T^{(n)}} = x^{T^{(n)}}\right). \tag{1.6}$$

Let

$$f_n(\omega) = -\frac{1}{|T^{(n)}|} \log P\left(X^{T^{(n)}}\right). \tag{1.7}$$

$f_n(\omega)$ will be called the entropy density of $X^{T^{(n)}}$, where log is the natural logarithm. If $\{X_t, t \in T\}$ is a T-indexed Markov chain with the state space S defined by Definition 1, we have by (1.5)

$$f_n(\omega) = -\frac{1}{|T^{(n)}|} [\log P(X_0) + \sum_{t \in T^{(n)} \setminus \{o\}} \log P_t(X_t | X_{1_t})]. \tag{1.8}$$

The convergence of $f_n(\omega)$ in a sense (L_1 convergence, convergence in probability, or almost sure convergence) is called the Shannon-McMillan theorem or the asymptotic equipartition property (AEP) in information theory. Shannon-McMillan theorems on the Markov chain have been studied extensively (see [4–7]). In the recent years, with the development of the information theory scholars get to study the Shannon-McMillan theorems for stochastic processes on the tree graph (see [8]). The tree models have recently drawn increasing interest from specialists in physics, probability and information theory. Berger and Ye (see [9]) have studied the existence of entropy rate for G-invariant random fields. Recently, Ye and Berger (see [10]) have also studied the ergodic property and Shannon-McMillan theorem for PPG-invariant random fields on trees. But their results only relate to convergence in probability. Liu and Yang (see [11]) have recently studied a.s.

convergence of Shannon-McMillan theorem for Markov chains indexed by a homogeneous tree and the generalized Cayley tree. Huang (see [12]) have discussed some strong laws of large numbers for Markov chains indexed by an infinite tree with uniformly bounded degree. Yang and Ye (see [13]) have studied the asymptotic equipartition property for nonhomogeneous Markov chains indexed by the homogeneous tree. Wang (see [7, 14–22]) have also studied the asymptotic equipartition property for mth-order nonhomogeneous Markov chains and some limit properties for nonhomogeneous Markov chains and Markov chains field.

In this paper, we study the generalized Shannon-McMillan theorems for nonhomogeneous Markov chains indexed by an infinite tree with the uniformly bounded degree by using the tools of the consistent distribution functions and a nonnegative super-martingale. As corollaries, some Shannon-McMillan theorems for Markov chains indexed by a homogeneous tree and the general nonhomogeneous Markov chain are obtained. Liu and Yang's (see [4, 13]) results are extended.

2 Main Results and Its Proof

Theorem 2.1. *Let T be an infinite tree with a uniformly bounded degree. Let $X = \{X_t, t \in T\}$ be a T-indexed Markov chain with the state space S defined as before, $\{a_t, t \in T\}$ an arbitrary nonnegative increasing stochastic sequence. Denote by $H_t(\omega)$ the random conditional entropy of X_t relative to X_{1_t}, that is*

$$H_t(\omega) = -\sum_{x_t \in S} P_t(x_t|X_{1_t}) \log P_t(x_t|X_{1_t}), \quad t \in T^{(n)} \backslash \{o\}. \tag{2.1}$$

If

$$\lim_{n\to\infty} \sum_{t \in T^{(n)} \backslash \{o\}} \frac{1}{a_t^2} < \infty. \quad a.s. \tag{2.2}$$

Then

$$\lim_{n\to\infty} \sum_{t \in T^{(n)} \backslash \{o\}} \frac{\log P_t(X_t|X_{1_t}) + H_t(\omega)}{a_t} < \infty. \quad a.s. \tag{2.3}$$

$$\lim_{n\to\infty} \frac{1}{a_{|T^{(n)}|}} \sum_{t \in T^{(n)} \backslash \{o\}} [\log P_t(X_t|X_{1_t}) + H_t(\omega)] = 0, \quad a.s. \tag{2.4}$$

where $|T^{(n)}|$ represents the number of all the vertices from level 0 to level n.

Proof. On the probability space $(\Omega, \mathcal{F}, \mathcal{P})$, let $\lambda = 1$ or $\lambda = -1$. Denote

$$\mu_Q(\lambda; x^{T^{(n)}}) = \frac{p(x_0) \prod_{t \in T^{(n)} \backslash \{o\}} P_t(x_t|x_{1_t}) \exp\left\{\frac{\lambda(\log P_t(x_t|x_{1_t}) + H_t(\omega))}{a_t}\right\}}{\prod_{t \in T^{(n)} \backslash \{o\}} U_t(\lambda; x_t)}, \quad n \geq 1, \tag{2.5}$$

where

$$U_t(\lambda;x_t) = E\left\{\exp\left\{\frac{\lambda(\log P_t(X_t|X_{1_t}) + H_t(\omega))}{a_t}\right\}|X_{1_t} = x_{1_t}\right\} \tag{2.6}$$
$$= \sum_{x_t\in S}\exp\left\{\frac{\lambda(\log P_t(x_t|x_{1_t}) + H_t(\omega))}{a_t}\right\}\cdot P_t(x_t|x_{1_t}).\quad t\in T^{(n)}\backslash\{o\}.$$

By (2.5) and (2.6), when $n \geq 1$,

$$\sum_{x^{L_n}\in S^{L_n}}\mu_Q\left(\lambda;x^{T^{(n)}}\right)$$
$$= \sum_{x^{L_n}\in S^{L_n}}\frac{p(x_0)\prod\limits_{t\in T^{(n)}\backslash\{o\}}P_t(x_t|x_{1_t})\exp\left\{\frac{\lambda(\log P_t(x_t|x_{1_t})+H_t(\omega))}{a_t}\right\}}{\prod_{t\in T^{(n)}\backslash\{o\}}U_t(\lambda;x_t)}$$
$$= \mu_Q\left(\lambda;x^{T^{(n-1)}}\right)\frac{\sum\limits_{x^{L_n}\in S^{L_n}}\prod\limits_{t\in L_n}P_t(x_t|x_{1_t})\exp\left\{\frac{\lambda(\log P_t(x_t|x_{1_t})+H_t(\omega))}{a_t}\right\}}{\prod_{t\in L_n}U_t(\lambda;x_t)}$$
$$= \mu_Q\left(\lambda;x^{T^{(n-1)}}\right)\frac{\prod\limits_{t\in L_n}\sum\limits_{x_t\in S}P_t(x_t|x_{1_t})\exp\left\{\frac{\lambda(\log P_t(x_t|x_{1_t})+H_t(\omega))}{a_t}\right\}}{\prod_{t\in L_n}U_t(\lambda;x_t)}$$
$$= \mu_Q\left(\lambda;x^{T^{(n-1)}}\right)\frac{\prod_{t\in L_n}U_t(\lambda;x_t)}{\prod_{t\in L_n}U_t(\lambda;x_t)} = \mu_Q\left(\lambda;x^{T^{(n-1)}}\right).\quad a.s. \tag{2.7}$$

Define $\mu_Q(\lambda;x^{T^{(0)}}) = p(x_0)$, then

$$\sum_{x_0\in S}\mu_Q\left(\lambda;x^{T^{(0)}}\right) = \sum_{x_0\in S}p(x_0) = 1.$$

Therefore $\mu_Q(\lambda;x^{T^{(n)}})$, $n = 0,1,2,...$ are a family of consistent distribution functions on $S^{T^{(n)}}$. Let

$$T_n(\lambda,\omega) = \frac{\mu_Q(\lambda;X^{T^{(n)}})}{P(X^{T^{(n)}})}. \tag{2.8}$$

By (1.5), (2.5) and (2.8), we have

$$T_n(\lambda,\omega) = \frac{\exp\left\{\sum\limits_{t\in T^{(n)}\backslash\{o\}}\frac{\lambda(\log P_t(X_t|X_{1_t})+H_t(\omega))}{a_t}\right\}}{\prod\limits_{t\in T^{(n)}\backslash\{o\}}U_t(\lambda;X_t)},\quad n\geq 0. \tag{2.9}$$

It is easy to see that $T_n(\lambda,\omega)$ is a nonnegative sup-martingale from Doob's martingale convergence theorem (see [23]). Therefore, we obtain by (2.8)

$$\lim_{n\to\infty}T_n(\lambda,\omega) = T_\infty(\lambda,\omega) < \infty.\quad a.s.\ \ \omega\in D(\omega) \tag{2.10}$$

Denote $P_t(x_t|X_{1_t})$ by P_t in brief, by (2.1) we have

$$\sum_{x_t\in S}\frac{\lambda[\log P_t(x_t|X_{1_t})+H_t(\omega)]}{a_t}\cdot P_t(x_t|X_{1_t})=\frac{\lambda[H_t(\omega)-H_t(\omega)]}{a_t}=0. \qquad (2.11)$$

By (2.6), (2.11) and the inequality $0\le e^x-1-x\le(1/2)x^2e^{|x|}$, the entropy density inequality $H_t(\omega)\le\log N$, noticing that $\lambda=\pm1$, we have

$$\begin{aligned}0&\le U_t(\lambda;X_t)-1\\&=\sum_{x_t\in S}\left\{\exp\left\{\frac{\lambda(\log P_t+H_t(\omega))}{a_t}\right\}-1-\frac{\lambda(\log P_t+H_t(\omega))}{a_t}\right\}P_t\\&\le\frac{1}{2a_t^2}\sum_{x_t\in S}(\log P_t+H_t(\omega))^2\exp\left\{\frac{|\log P_t+H_t(\omega)|}{a_t}\right\}P_t\\&\le\frac{1}{2a_t^2}\sum_{x_t\in S}(\log P_t+H_t(\omega))^2\exp\left\{\frac{-\log P_t+\log N}{a_t}\right\}P_t.\quad a.s.\end{aligned} \qquad (2.12)$$

It is easy to see $a_t\to\infty$, $t\to\infty$ ($as\ n\to\infty$) from (2.2), there exists a positive integer m such that $a_t\ge2$ as $t\ge m$. Hence as $t\ge m$, by (2.12) and the entropy density inequality, we obtain

$$\begin{aligned}0&\le U_t(\lambda;X_t)-1\\&\le\frac{1}{2a_t^2}\sum_{x_t\in S}(\log P_t+H_t(\omega))^2\exp\left\{\frac{-\log P_t+\log N}{2}\right\}P_t\\&\le\frac{1}{2a_t^2}\sum_{x_t\in S}(\log P_t+H_t(\omega))^2\exp\{\log(N/P_t)^{1/2}\}P_t\\&\le\frac{N}{2a_t^2}\sum_{x_t\in S}(\log P_t+H_t(\omega))^2P_t^{1/2}\\&\le\frac{N}{2a_t^2}\sum_{x_t\in S}[(\log P_t)^2P_t^{1/2}+2H_t(\omega)\cdot P_t^{1/2}\log P_t+(H_t(\omega))^2]\\&\le\frac{N}{2a_t^2}\sum_{x_t\in S}[(\log P_t)^2P_t^{1/2}-2\log N\cdot P_t^{1/2}\log P_t+(\log N)^2].\quad a.s.\end{aligned} \qquad (2.13)$$

It is easy to calculate

$$\max\{x^{1/2}(\log x)^2,\ 0<x\le1\}=16e^{-2};$$

$$\max\{-x^{1/2}\log x,\ 0<x\le1\}=2e^{-1}.$$

By (2.2) and (2.13), we have

$$\begin{aligned}
&\sum_{t\in T^{(n)}\setminus\{o\}}(U_t(\lambda;X_t)-1)\\
&\quad\le \sum_{t\in T^{(n)}\setminus\{o\}}\frac{N}{2a_t^2}\sum_{x_t\in S}[(\log P_t)^2P_t^{1/2}-2\log N\cdot P_t^{1/2}\log P_t+(\log N)^2]\\
&\quad\le \sum_{t\in T^{(n)}\setminus\{o\}}\sum_{x_t\in S}\frac{N}{2a_t^2}[16e^{-2}+2(\log N)2e^{-1}+(\log N)^2]\\
&\quad= \sum_{t\in T^{(n)}\setminus\{o\}}\frac{N^2}{2a_t^2}[16e^{-2}+4(\log N)e^{-1}+(\log N)^2]<\infty,\quad a.s.\ \ \omega\in D(\omega).
\end{aligned} \tag{2.14}$$

By the convergence theorem of infinite production, (2.14) implies that

$$\lim_{n\to\infty}\prod_{t\in T^{(n)}\setminus\{o\}}U_t(\lambda;X_t)\quad \textit{converges}\quad a.s.\ \ \omega\in D(\omega). \tag{2.15}$$

By (2.9), (2.10) and (2.15), we obtain

$$\lim_{n\to\infty}\exp\left\{\sum_{t\in T^{(n)}\setminus\{o\}}\frac{\lambda(\log P_t(X_t|X_{1_t})+H_t(\omega))}{a_t}\right\}=a\text{ finite number}\ \ a.s.\ \omega\in D(\omega). \tag{2.16}$$

Letting $\lambda=1$ and $\lambda=-1$ in (2.16), respectively, we have

$$\lim_{n\to\infty}\exp\left\{\sum_{t\in T^{(n)}\setminus\{o\}}\frac{\log P_t(X_t|X_{1_t})+H_t(\omega)}{a_t}\right\}=a\text{ finite number}\ \ a.s.\ \omega\in D(\omega). \tag{2.17}$$

$$\lim_{n\to\infty}\exp\left\{\sum_{t\in T^{(n)}\setminus\{o\}}\frac{-(\log P_t(X_t|X_{1_t})+H_t(\omega))}{a_t}\right\}=a\text{ finite number}\ \ a.s.\ \omega\in D(\omega). \tag{2.18}$$

(2.17) and (2.18) imply that

$$\lim_{n\to\infty}\sum_{t\in T^{(n)}\setminus\{o\}}\frac{\log P_t(X_t|X_{1_t})+H_t(\omega)}{a_t}\quad\text{converges}\quad a.s.\ \ \omega\in D(\omega). \tag{2.19}$$

Hence (2.3) holds. By (2.19) and Kronecker's lemma, we have

$$\lim_{n\to\infty}\frac{1}{a_{|T^{(n)}|}}\sum_{t\in T^{(n)}\setminus\{o\}}[\log P_t(X_t|X_{1_t})+H_t(\omega)]=0\quad a.s.\ \ \omega\in D(\omega). \tag{2.20}$$

□

3 Some Shannon-McMillan Theorems for Nonhomogeneous Markov Chains on the Homogeneous Tree

Corollary 3.1. *Let $X = \{X_t, t \in T\}$ be a nonhomogeneous Markov chain indexed by a homogeneous tree, $f_n(\omega)$ and $H_k(\omega)$ be defined as* (1.8) *and* (2.1)*. Then*

$$\lim_{n\to\infty} \sum_{t\in T^{(n)}\setminus\{o\}} \frac{[\log P_t(X_t|X_{1_t}) + H_t(\omega)]}{t} < \infty, \quad a.s. \tag{3.1}$$

$$\lim_{n\to\infty} [f_n(\omega) - \frac{1}{|T^{(n)}|} \sum_{t\in T^{(n)}\setminus\{o\}} H_t(\omega)] = 0. \quad a.s. \tag{3.2}$$

Proof. Let T be a homogeneous tree, that is on the tree each vertex has M neighboring vertices. Let $a_t = t,\ t \in T^{(n)}$, then $\lim\limits_{n\to\infty} \sum\limits_{t\in T^{(n)}\setminus\{o\}} \frac{1}{a_t^2} < \infty$ holds obviously, we obtain $a_{|T^{(n)}|} = |T^{(n)}|$, by (1.8), (2.4) we get

$$\begin{aligned} \lim_{n\to\infty} \frac{1}{a_{|T^{(n)}|}} & \sum_{t\in T^{(n)}\setminus\{o\}} [\log P_t(X_t|X_{1_t}) + H_t(\omega)] \\ &= -\lim_{n\to\infty} \frac{1}{|T^{(n)}|} \sum_{t\in T^{(n)}\setminus\{o\}} [-\log P_t(X_t|X_{1_t}) - H_t(\omega)] \\ &= -\lim_{n\to\infty} [f_n(\omega) - \frac{1}{|T^{(n)}|} \sum_{t\in T^{(n)}\setminus\{o\}} H_t(\omega)] = 0, \quad a.s. \end{aligned} \tag{3.3}$$

(3.1), (3.2) follow from (2.3), (2.4) directly. □

Remark 3.2. *Equation* (3.2) *is a result of Yang and Ye (see [13]).*

Corollary 3.3. *Let $X = \{X_t, t \in T\}$ be a T-indexed Markov chain with the state space S, $H_t(\omega)$ defined as before. Denote $p > 1/2$, then*

$$\lim_{n\to\infty} \sum_{t\in T^{(n)}\setminus\{o\}} \frac{\log P_t(X_t|X_{1_t}) + H_t(\omega)}{t^{1/2}(\log t)^p} < \infty. \quad a.s. \tag{3.4}$$

$$\lim_{n\to\infty} \frac{1}{|T^{(n)}|^{1/2}(\log |T^{(n)}|)^p} \sum_{t\in T^{(n)}\setminus\{o\}} [\log P_t(X_t|X_{1_t}) + H_t(\omega)] = 0. \quad a.s. \tag{3.5}$$

Proof. Let $a_t = t^{1/2}(\log t)^p,\ t \in T^{(n)}$, then $\lim_{n\to\infty} \sum_{t\in T^{(n)}\setminus\{o\}} \frac{1}{t(\log t)^{2p}} < \infty$ holds obviously. we obtain (3.4), (3.5) from (2.3), (2.4), respectively. □

When the successor of each vertex on the infinite tree with the uniformly bounded degree has only one vertex, the nonhomogeneous Markov chain on the tree degenerates into the general nonhomogeneous Markov chain.

Corollary 3.4. *Let $\{X_n, n \geq 0\}$ be a nonhomogeneous Markov chain with the initial distribution and the transition probabilities as follows:*

$$p(i) > 0, \quad i \in S.$$

$$P_t(j|i) > 0, \quad i, j \in S, \quad t = 1, 2, ... \tag{3.6}$$

Set

$$f_n(\omega) = -\frac{1}{n+1}\left[\log P(X_0) + \sum_{t=1}^{n} \log P_t(X_t|X_{t-1})\right], \tag{3.7}$$

$$H_t(\omega) = -\sum_{x_t \in S} P_t(x_t|X_{t-1}) \log P_t(x_t|X_{t-1}). \tag{3.8}$$

Then

$$\sum_{t=1}^{\infty} \frac{\log P_t(X_t|X_{t-1}) + H_t(\omega)}{t} < \infty, \quad a.s. \tag{3.9}$$

$$\lim_{n\to\infty}\left[f_n(\omega) - \frac{1}{n+1}\sum_{t=1}^{n} H_t(\omega)\right] = 0. \quad a.s. \tag{3.10}$$

Proof. At this time the nonhomogeneous Markov chain $X = \{X_t, t \in T\}$ indexed by the infinite tree is changed into the general nonhomogeneous Markov chain $\{X_n, n \geq 0\}$, we obtain $P_t(X_t|X_{1_t}) = P_t(X_t|X_{t-1})$, $|T^{(n)}| = n + 1$. (3.7)-(3.10) follow from (1.8), (2.1), (3.1) and (3.2), respectively. □

Remark 3.5. *Equation* (3.10) *is just Theorem 2 of Liu and Yang (see [4]).*

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