ADAPTIVE ENCODING AND PREDICTION OF HIDDEN MARKOV PROCESSES

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Abstract

The purpose of this paper is to provide explicit results on the almost sure asymptotic performance of adaptive encoding and prediction procedures for finite-state Hidden Markov Models. In addition, Rissanen's tail condition [14] will be verified, from which a lower bound for the mean-performance of universal encoding procedures will be derived. The results of this paper are based on [10].

1 Introduction

Hidden Markov Models have become a basic tool for modeling stochastic systems with a wide range of applicability. For a general introduction see [16]. The estimation of the dynamics of a Hidden Markov Model is a basic problem in applications. A key element in the statistical analysis of HMM-s is a strong law of large numbers for the log-likelihood function, see [11], [12], [3]. An alternative tool that has been widely used in linear system identification is theory of L-mixing processes. The relevance of this theory is established in [10] using a random-transformation representation for Markov-processes (see [9]). The advantage of this approach is that, under suitable conditions a more precise characterization of the estimation error-process can be obtained, which, in turn, is crucial for the analysis of the performance of adaptive prediction, see [6].

The purpose of this paper is to provide explicit results on the almost sure asymptotic performance of adaptive encoding and prediction procedures for finite-state Hidden Markov Models. In addition, Rissanen's tail condition [14] will be verified, from which a lower bound for the mean-performance of universal encoding procedures will be derived.

2 Hidden Markov Models

We consider Hidden Markov Models with a general state space $\mathcal{X}$ and a general observation or read-out space $\mathcal{Y}$. Both are assumed to be Polish spaces, i.e. they are complete, separable metric spaces.

Definition 2.1 *The pair (X_n, Y_n) is a Hidden Markov process if (X_n) is a homogenous Markov chain, with state space $\mathcal{X}$ and the observations (Y_n) are conditionally independent and identically distributed given (X_n).*

If $\mathcal{X}$ and $\mathcal{Y}$ are finite, say $|\mathcal{X}| = N$, $|\mathcal{Y}| = M$, then we have

$$P(Y_n = y_n, \dots Y_0 = y_0 | X_n = x_n, \dots X_0 = x_0) =$$

$$\prod_{i=0}^{n} P(Y_i = y_i | X_i = x_i).$$

In this case we will use the following notations

$$P(Y_k = y | X_k = x) = b^{*x}(y), \quad B^*(y) = \mathrm{diag}(b^{*i}(y)),$$

where $i = 1, \dots, N$, and $*$ indicates that we take the true value of the corresponding unknown quantity.

Let Q^* be the transition matrix of the unobserved Markov process (X_n), i.e.

$$Q^*_{ij} = P(X_{n+1} = j | X_n = i).$$

A key quantity in estimation theory is the predictive filter defined by

$$p^{*j}_{n+1} = P(X_{n+1} = j | Y_n, \dots, Y_0). \tag{1}$$

Writing $p^*_{n+1} = (p^{*1}_{n+1}, \dots, p^{*N}_{n+1})^T$, the filter process satisfies the Baum-equation

$$p^*_{n+1} = \pi(Q^{*T} B^*(Y_n) p^*_n), \tag{2}$$

where π is the normalizing operator: for $x \geq 0$, $x \neq 0$ set $\pi(x)^i = x^i / \sum_j x^j$, see [1]. Here $p^{*j}_0 = P(X_0 = j)$.

In practice, the transition probability matrix Q^* and the initial probability distribution p^*_0 of the unobserved Markov chain (X_n) and the conditional probabilities $b^{*i}(y)$ of the observation sequence (Y_n) are possibly unknown. For this reason we consider the Baum-equation in a more general sense

$$p_{n+1} = \pi(Q^T B(Y_n) p_n), \tag{3}$$

with initial condition $p_0 = q$, where Q is a stochastic matrix, p_n is a probability vector on $\mathcal{X}$, and $B(y) = \mathrm{diag}(b^i(y))$ is a collection of conditional probabilities.

Continuous read-outs will be defined by taking the following conditional densities:

$$P(Y_n \in dy | X_n = x) = b^{*x}(y)\lambda(dy),$$

where λ is a fixed nonnegative, σ-finite measure. Let

$$B^*(y) = \mathrm{diag}(b^{*i}(y)),$$

where $i = 1, \ldots, N$, then the conditional probability defined under 1 will satisfy the Baum-equation. In the rest of the section we deal with continuous read-out, which includes the finite case in a natural manner.

We will take an arbitrary probability vector q as initial condition, and the solution of the Baum equation will be denoted by $p_n(q)$.

A key property of the Baum equation is its exponential stability with respect to the initial condition. This has been established in [11] for continuous read-outs. Here we state the result for HMM-s with a positive transition probability matrix:

Proposition 2.1 *Assume that $Q > 0$ and $b^x(y) > 0$ for all x, y. Let q, q' be any two initializations. Then*

$$\|p_n(q) - p_n(q')\|_{TV} \leq C(1-\delta)^n \|q - q'\|_{TV}, \qquad (4)$$

where $\| \quad \|_{TV}$ denotes the total variation norm and $0 < \delta < 1$.

If Q is only primitive, i.e. $Q^r > 0$ with some positive integer $r > 1$, then (4) holds with a random C.

Next we are going to introduce the notion of Doeblin-condition (see [2]):

Definition 2.2 *If there exists an integer $m \geq 1$ such that $P^m(x, A) \geq \delta\nu(A)$ is valid for all $x \in \mathcal{X}$ and $A \in \mathcal{B}(\mathcal{X})$ with some probability measure ν, then we say that the Doeblin-condition is satisfied.*

Now let (X_n, Y_n) be a Hidden Markov process and assume that the state space $\mathcal{X}$ and the observed space $\mathcal{Y}$ are Polish.

Lemma 2.1 *Assume that the Doeblin condition holds for the Markov chain (X_n). Then the Doeblin condition holds for (X_n, Y_n) as well.*

3 Markov chains and L-mixing processes

Now we are going to introduce a class of processes called L-mixing processes which have been used extensively in the statistical analysis of linear stochastic systems, see [5].

Definition 3.1 *A stochastic process (X_n) ($n \geq 0$) taking its values in an Euclidean space is M-bounded if for all $q \geq 1$*

$$M_q = \sup_{n \geq 0} E^{1/q} \|X_n\|^q < \infty.$$

Let $(\mathcal{F}_n)$ and $(\mathcal{F}_n^+)$ be two sequences of monoton increasing and monoton decreasing σ-algebras, respectively such that $\mathcal{F}_n$ and $\mathcal{F}_n^+$ are independent for all n.

Definition 3.2 *A stochastic process (X_n) taking its values in a finite-dimensional Euclidean space is L-mixing, if it is M-bounded and with*

$$\gamma_q(\tau) = \sup_{n \geq \tau} E^{1/q} \|X_n - E(X_n | \mathcal{F}_{n-\tau}^+)\|^q$$

we have

$$\Gamma(q) = \sum_{\tau=0}^{\infty} \gamma_q(\tau) < \infty.$$

The following proposition shows the importance of the L-mixing processes.

Proposition 3.1 *Let (X_n) be a Markov chain with state space $\mathcal{X}$, where $\mathcal{X}$ is a Polish space, and assume that the Doeblin condition is valid for $m = 1$. Furthermore let $g : \mathcal{X} \longrightarrow \mathbb{R}$ be a bounded, measurable function. Then $g(X_n)$ is an L-mixing process.*

4 Estimation of Hidden Markov Models

This section gives a brief outline of the maximum likelihood estimation of Hidden Markov Models. Consider a Hidden Markov Process (X_n, Y_n), where the state space $\mathcal{X}$ is finite and the observation space $\mathcal{Y}$ is continuous, a measurable subset of $\mathbb{R}^d$. Assume that the transition probability matrix and the conditional read-out densities are positive, i.e. $Q^* > 0$ and $b^{*i} > 0$ for all i, y. Then the process (X_n, Y_n) satisfies the Doeblin-condition.

Let the invariant distribution of $\mathcal{X}$ be ν and the invariant distribution of $\mathcal{X} \times \mathcal{Y}$ be π. Then

$$\pi^i(dy) = \nu_i b^{*i}(y)\lambda(dy), \qquad (5)$$

where π^i denotes the components of π. Furthermore let the running value of the transition probability matrix Q and the running value of the conditional read-out densities be also positive, i.e. $Q > 0$, $b^i(y) > 0$, respectively.

With the notation $p_n^i = P(X_n = i | Y_{n-1}, \ldots, Y_0)$ we have

$$p_{n+1} = \pi(Q^T B(Y_n) p_n) = f(Y_n, p_n).$$

We use capital letters for random variables and lower cases for their realizations, i.e. X is a random variable and x is a realization of X. The only exception is p, where the meaning depends on the context.

The logarithm of the likelihood function is

$$\sum_{k=1}^{n-1} \log p(y_k | y_{k-1}, \ldots y_0, \theta) + \log p(y_0, \theta).$$

Here the k-th term for $k \geq 1$ can be written as

$$\log \sum_i b^i(y_k) P(i|y_{k-1}, \ldots, y_0, \theta) = \log \sum_i b^i(y_k) p_k^i.$$

Now write

$$g(y,p) = \log \sum_i b^i(y) p^i, \tag{6}$$

then we have

$$\log p(y_N, \ldots, y_0, \theta) = \sum_{k=1}^{N} g(y_k, p_k) + \log p(y_0, \theta). \tag{7}$$

It is easy to see that the Doeblin condition is not satisfied for the process (X_n, Y_n, p_n), thus Proposition 3.1 is not applicable directly. For this reason we look for a different characterization of (X_n, Y_n, p_n).

Theorem 4.1 *Consider a Hidden Markov Model (X_n, Y_n), where the state space $\mathcal{X}$ is finite and the observation space $\mathcal{Y}$ is continuous, a measurable subset of $\mathbb{R}^d$. Let $Q, Q^* > 0$ and $b^i(y), b^{*i}(y) > 0$ for all i, y. Let the initialization of the process (X_n, Y_n) be random, where the Radon-Nikodym derivate of the initial distribution π_0 w.r.t the stationary distribution π is bounded, i.e.*

$$\frac{d\pi_0}{d\pi} \leq K. \tag{8}$$

Assume that for all $i, j \in \mathcal{X}$

$$\int |\log b^j(y)|^q b^{*i}(y) \lambda(dy) < \infty. \tag{9}$$

Then the process $g(Y_n, p_n)$ is L-mixing.

Remark 4.1 *Since the positivity of Q implies that the stationary distribution of (X_n) is strictly positive in every state and the densities of the read-outs are strictly positive Condition (8) is not a strong condition. For example for the random initialization we can take a uniform distribution on $\mathcal{X}$ and an arbitrary set of λ a.e. positive density functions $b_0^i(y)$.*

To analyze the asymptotic properties of the right hand side of (7) Theorem 4.1 seems to be relevant. Under the conditions of Theorem 4.1 $g(y,p)$ is an L-mixing process and the law of large numbers is valid for such processes, see [5]. This implies the existence of the limit of (7).

Consider now a *finite state-finite read-out* HMM. This case follows from Theorem 4.1, but the integrability condition (9) is simplified due to the discrete measure.

Theorem 4.2 *Consider the Hidden Markov Model (X_n, Y_n), where $\mathcal{X}$ and $\mathcal{Y}$ are finite. Assume that the process (X_n, Y_n) satisfies the Doeblin condition. Let the running value of the transition probability matrix Q be positive and $b^i(y) \geq \delta > 0$ for all i, y. Then with a random initialization on $\mathcal{X} \times \mathcal{Y}$ we have that $g(Y_n, p_n)$ is an L-mixing process.*

Consider a finite state-finite read-out HMM, parameterized by θ, where $|\mathcal{X}| = N$ and $|\mathcal{Y}| = M$ and θ containing the elements of the transition probability matrix and the read-out probabilities. Thus θ is an $N^2 + NM - 2N$ dimensional vector with coordinates between 0 and 1. Furthermore let the ML estimate of the true parameter θ^* be denoted by $\hat{\theta}_N$. Due to [11] the gradient process $\partial p_n(\theta)/\partial\theta$ is also exponentially stable, thus the process $\partial g(Y_n, p_n(\theta))/\partial\theta$ is an L-mixing process, see [10]. Similarly it can be shown that $\partial^2 g(Y_n, p_n(\theta)/\partial\theta^2$ is also an L-mixing process. The arguments of [6] yield the following result.

Theorem 4.3 *Consider the Hidden Markov Model (X_n, Y_n), where $\mathcal{X}$ and $\mathcal{Y}$ are finite. Let $Q, Q^* > 0$ and $b^i(y) \geq \delta$, $b^{*i}(y) \geq \delta$ for all i, y, where $\delta > 0$. Let $\hat{\theta}_N$ be the ML estimate of θ^*. Then $\hat{\theta}_N - \theta^*$ can be written as*

$$-(I(\theta^*)^{-1} \frac{1}{N} \sum_{n=1}^{N} \frac{\partial}{\partial\theta} \log p(Y_n|Y_{n-1}, \ldots, Y_0, \theta^*) + r_n, \tag{10}$$

where $r_n = O_M(N^{-1})$, i.e Nr_n is M-bounded, and $I(\theta^*)$ is the Fisher-information matrix.

A key point here is that the error term is $O_M(N^{-1})$. This ensures that all basic limit theorems, that are known for the dominant term, which is a martingale, are also valid for $\hat{\theta}_N - \theta^*$.

Next we are going to prove that the tail-condition in Rissanen-theorem, see in [14], for the error term of the estimation θ is satisfied.

Theorem 4.4 *Under the condition of Theorem 4.3 we have*

$$\sum_{N=1}^{\infty} P(N^{\frac{1}{2}}(\hat{\theta}_N - \theta^*) > c \log N)) < \infty,$$

where $c > 0$ is an arbitrary constant

Proof: Let

$$J_n = \sum_{i=1}^{n} \frac{\partial}{\partial\theta} \log p(Y_i|Y_{i-1}, \ldots, Y_0, \theta)_{|\theta=\theta^*}$$

Then (J_n) is a martingale, and $\sup(J_n - J_{n-1})$ is

$$\frac{\partial}{\partial\theta} \log p(y_n|y_{n-1}, \ldots, y_0, \theta)_{|\theta=\theta^*} \leq c \tag{11}$$

with some positive constant $c > 0$. Let the martingale (J_n) be $\mathcal{G}_n$-adapted. Furthermore let (A_n) denote the increasing process associated with the submartingale (J_n^2), making $J_n^2 - A_n$ a martingale. A_n has a form

$$A_n = \sum_{k=1}^{n} E((J_k - J_{k-1})^2 | \mathcal{G}_{k-1}).$$

Then (11) implies that

$$A_n \leq c'n \tag{12}$$

with some positive constant c'. The following very simple lemma is given in [13]:

Lemma 4.1 *Let J_n be a square-integrable martingale such that* $\sup(J_{n+1} - J_n) \le c$ *a.s., where $c > 0$. Then*

$$\exp(\lambda J_n - \mu A_n)$$

is a positive supermartingale, where λ is an arbitrary positive number, and μ is a positive number depending only on λ and c.

As a consequence of the lemma we have that

$$E \exp(\lambda J_n - \mu A_n) \le K.$$

Using (12) we have

$$E \exp(\lambda J_n - \mu c' n) \le K,$$

$$E \exp(\lambda J_n) \le \exp(c'' n), \tag{13}$$

where $e^{c"} = K e^{\mu c'}$.

Consider the process $\widehat{J}_n = \frac{1}{\sqrt{N}} J_n$ for an arbitrary fix N. Using inequality (13) for $\widehat{J}_n$ with the respective increasing associated process $\widehat{A}_n = \frac{A_n}{N}$ and $\widehat{c} = \frac{c}{N} < c$ at $n = N$ we have

$$E \exp(\lambda \frac{1}{\sqrt{N}} J_N) \le c''. \tag{14}$$

The last inequality and Markov's inequality imply that

$$P(\frac{1}{\sqrt{N}} J_N > d \log N) =$$

$$P(\exp(\lambda \frac{1}{\sqrt{N}} J_N) > \exp(\lambda d \log N)) \le \frac{c''}{N^{d\lambda}}.$$

Thus if $d\lambda > 1$ then

$$\sum_{N=1}^{\infty} P(\frac{1}{\sqrt{N}} J_N > d \log N) < \infty. \tag{15}$$

Using Theorem 4.3 we have

$$\frac{1}{\sqrt{N}} J_N = N^{\frac{1}{2}}(-I(\theta^*))(\hat{\theta}_N - \theta^*) + O_M(N^{-\frac{1}{2}}).$$

This implies that one term in the sum is

$$P(N^{\frac{1}{2}}(-I(\theta^*))(\hat{\theta}_N - \theta^*) + O_M(N^{-\frac{1}{2}}) > d \log N) <$$

$$P(N^{\frac{1}{2}}(\hat{\theta}_N - \theta^*) > \frac{d}{2} \log N) + P(O_M(N^{-\frac{1}{2}}) > \frac{d}{2} \log N),$$

and $P(O_M(N^{-\frac{1}{2}}) > \frac{d}{2} \log N) < C N^{-s}$ for all $s > 1$ thus we get that the second term is summable.

Using (15) this implies that

$$\sum_{N=1}^{\infty} P(N^{\frac{1}{2}}(\hat{\theta}_N - \theta^*) > \frac{d}{2} \log N) < \infty,$$

thus the tail probabilities are uniformly summable as stated in the theorem.

In the next section we are going to introduce some consequences of this result.

5 Encoding of finite state Hidden Markov Models

The negative logarithm of the conditional probability

$$-\log p(y_n | y_{n-1}, \ldots, y_1, \theta)$$

can be interpreted as a code length, see [15]. An adaptive encoding procedure is obtained if we set $\theta = \hat{\theta}_{n-1}$. Following [7] we get the following result:

Theorem 5.1 *Let s_n denote the loss in codelength:*

$$-\log p(y_n | y_{n-1}, \ldots, y_1, \hat{\theta}_{n-1}) + \log p(y_n | y_{n-1}, \ldots, y_1, \theta^*).$$

Under the conditions of Theorem 4.3 we have

$$E_{\theta^*}(s_n) = \frac{1}{2n} p(1 + o(1)),$$

where $p = \dim \theta$. Furthermore

$$\lim_{N \to \infty} \frac{1}{\log N} \sum_{n=1}^{N} s_n = \frac{p}{2}$$

with probability 1.

This result can be used for model selection for HMM-s, see [8], [4]. Due to the validity of Rissanen's tail condition the following "converse theorem" is also true by virtue of the fundamental theorem of the theory of stochastic complexity (cf. [14]):

Theorem 5.2 *Let $g_n(y_1, \ldots, y_n)$ be an arbitrary sequence of compatible probability distributions. Then*

$$\liminf_{n \to \infty} \frac{1}{\log n} E_\theta(-\log g_n(y_n, \ldots, y_1) + \log p(y_n, \ldots y_1, \theta))$$

is at least $p/2$ except for a set of θ's with Lebesgue-measure 0.

Theorem 5.1 can be extended to performance indexes different from the conditional entropy. Let (y_n) be a binary process taking value 0 or 1. Let e.g. $\hat{y}_n$ be the predictor defined by

$$\hat{y}_n(\theta) = \begin{cases} 1 & \text{if } q_n(\theta) = p(y_n = 1 | y_{n-1}, \ldots, y_1, \theta) > \frac{1}{2} \\ 0 & \text{otherwise.} \end{cases}$$

Define $q_n^* = P_{\theta^*}(Y_n = 1 | Y_{n-1}, \ldots, Y_1, \theta^*)$ and similarly $q_n = P_{\theta^*}(Y_n = 1 | Y_{n-1}, \ldots, Y_1, \theta)$. Then the failure probability can be expressed as

$$P_{\theta^*}(\hat{Y}_n(\theta) \ne Y_n) = \int_0^{1/2} (1 - q_n) q_n^* d\varphi_n(q_n(\theta)) +$$

$$\int_{1/2}^{1} (1 - q_n^*) q_n d\varphi_n(q_n(\theta)) = W_n(\theta),$$

where $d\varphi_n(q_n(\theta))$ is the distribution of $q_n(\theta)$ under P_{θ^*}.

Under the condition of Theorem 4.3 $\varphi_n(q_n(\theta))$ can be shown to converge in distribution to $\varphi(q(\theta))$ having an invariant distribution $\varphi(q,\theta)$. Let

$$W(\theta) = \lim_n W_n(\theta).$$

For finite n the function $W_n(\theta)$ is smooth in θ. Assuming that smoothness is inherited by $W(\theta)$ define

$$S^* = \frac{\partial^2}{\partial \theta^2} W(\theta)_{|\theta=\theta^*}.$$

The adaptive predictor of y_n is defined as

$$\hat{y}_n = \hat{y}_n(\hat{\theta}_{n-1}).$$

We have the following result:

Theorem 5.3 *Let the loss in prediction performance be*

$$T_n = P_{\theta^*}(\hat{Y}_n(\hat{\theta}_{n-1}) \neq Y_n) - P_{\theta^*}(\hat{Y}_n(\theta^*) \neq Y_n).$$

Under the conditions of Theorem 5.1 we have

$$E(T_n) = \frac{1}{2n}(\mathrm{Tr} S^* I(\theta^*)^{-1} + o(1)),.$$

Moreover

$$\lim_{N\to\infty} \frac{1}{\log N} \sum_{n=1}^{N} T_n = \mathrm{Tr} S^* I(\theta^*)^{-1}$$

with probability 1.

The invariant distribution of $\varphi(q(\theta))$ in exact form even in the simplest cases is unknown. Thus the theoretical value of $I(\theta^*)$ and S^* is unknown.

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