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## Heavy Tailed Hidden Semi-Markov Models

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### Abstract

Hidden semi-Markov models have been proposed in Meier-Hellstern et al (1991) to model the times between transmission of packets at a source. In this paper, we specifically investigate such models where the distributions associated with one or more of the states are heavy-tailed. We study the asymptotic properties of the sample covariance and correlation functions and show that the correlation function at nonzero lags is asymptotically equal to zero. Behavior of the sample autocorrelation function (acf) for a simulated five state semi-Markov model is contrasted with the behavior of the sample acf for a real data set in order to infer that the real data cannot be modeled by a hidden semi-Markov scheme.

### 1 Introduction.

Hidden semi-Markov models have often been used in speech recognition and computational biology; see Krogh et al (1994) and Juang and Rabiner (1991) for reviews. Such models have also often been proposed in the teletraffic literature. In the heavy tailed context, they were recently used by Meier-Hellstern et al (1991) to model the times between transmission of packets at a source. In the process of fitting these models to the data, it was observed that the distributions associated with one or more of the states of the model were heavy-tailed.

In this paper, we investigate hidden semi-Markov models where the distributions associated with one or more of the states are heavy-tailed. Our goal is to study the asymptotic properties of the sample covariance and autocorrelation function (acf) which are important for parameter estimation and fitting of actual data to such models. We use point process techniques to show that the sample correlation function at nonzero lags is asymptotically equal to zero.

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The plan of the paper is as follows: In Section 2, we give a detailed description of the model and construct a stationary version. In Section 3, we prove several convergence results for point processes associated with the model with the aim of studying the asymptotic properties of the sample covariance and correlation functions. In Section 4, we prove the major result of the paper, that the sample correlation function at nonzero lags is asymptotically equal to zero. In Section 5, we offer some numerical illustrations and some concluding remarks.

The reason for the interest in the sample autocorrelation function is the following. Examination of heavy tailed data frequently reveals the characteristic that the acf plots for different subsets of the data do not look similar. Some examples are given in Resnick (1997). Various explanations for this phenomenon are possible: maybe the data exhibits lack of stationarity or maybe the underlying model is non-linear. The following plot, from Davis and Resnick (1996) shows an extreme case: Plots of the acf from independent samples of the same stationary nonlinear process look completely different.

Subset analysis of the acf of a data set is often sufficient to rule out the iid or linear time series models as candidate models for fitting to the data. We were curious to see if the hidden Markov model was a possibility and hence set out to investigate the asymptotic behavior of the sample acf. Unfortunately our results rule out hidden Markov models as well since the behavior of the acf for such models is asymptotically the same as for the iid model. Unless one gives up finite mean sojourn times (and thus it is likely one must also give up stationarity) such models will be difficult to fit to data whose sample acf fails to exhibit subset stability. This point is further illustrated in Section 5.

## 2 The model.

Let  $\{J_n, n \geq 0\}$  be an ergodic Markov chain with state space  $\{1, \dots, p\}$ . Let the transition probability matrix of this chain be  $P = \{p_{ij}, 1 \leq i, j \leq p\}$  and the stationary distribution be  $\pi' = (\pi_1, \dots, \pi_p)$ . Suppose for  $i = 1, \dots, p$  we are given holding time distributions  $\{q_n^{(i)}\}$  concentrating on  $\{1, 2, \dots\}$  and that for  $i = 1, \dots, p$ ,  $\{D_n^{(i)}, n \geq 0\}$  are iid with common distribution  $\{q_n^{(i)}\}$  and further,  $E[q_n^{(i)}] = \tau_i < \infty$ . The sequences

$$\{\{D_n^{(i)}, i = 1, \dots, p\}$$

are independent. Define the semi-Markov chain  $\{V_n, n \geq 0\}$  by

$$\begin{aligned} V_j &= J_0, \text{ if } 0 \leq j < D_0^{(J_0)}, \\ &= J_1, \text{ if } D_0^{(J_0)} \leq j < D_0^{(J_0)} + D_1^{(J_1)}, \\ &= J_2, \text{ if } D_0^{(J_0)} + D_1^{(J_1)} \leq j < D_0^{(J_0)} + D_1^{(J_1)} + D_2^{(J_2)}, \\ &\vdots \end{aligned}$$

Thus

$$V_j = \sum_{k=0}^{\infty} J_k 1_{\{\sum_{i=0}^{k-1} D_i^{(J_i)} \leq j < \sum_{i=0}^k D_i^{(J_i)}\}}$$

The observable process  $\{X_n\}$  consists of random elements of  $\mathbb{R}_+$  defined on  $\{V_n\}$  such that the conditional distribution of  $X_n$  given the state of  $V_n$  is  $F_i$ . More precisely, given distributions  $F_1, \dots, F_p$  on  $\mathbb{R}_+$  and iid uniform random variables with support  $[0, 1]$  which we call  $\{U_n, n \geq 0\}$ , we then define for  $n \geq 0$

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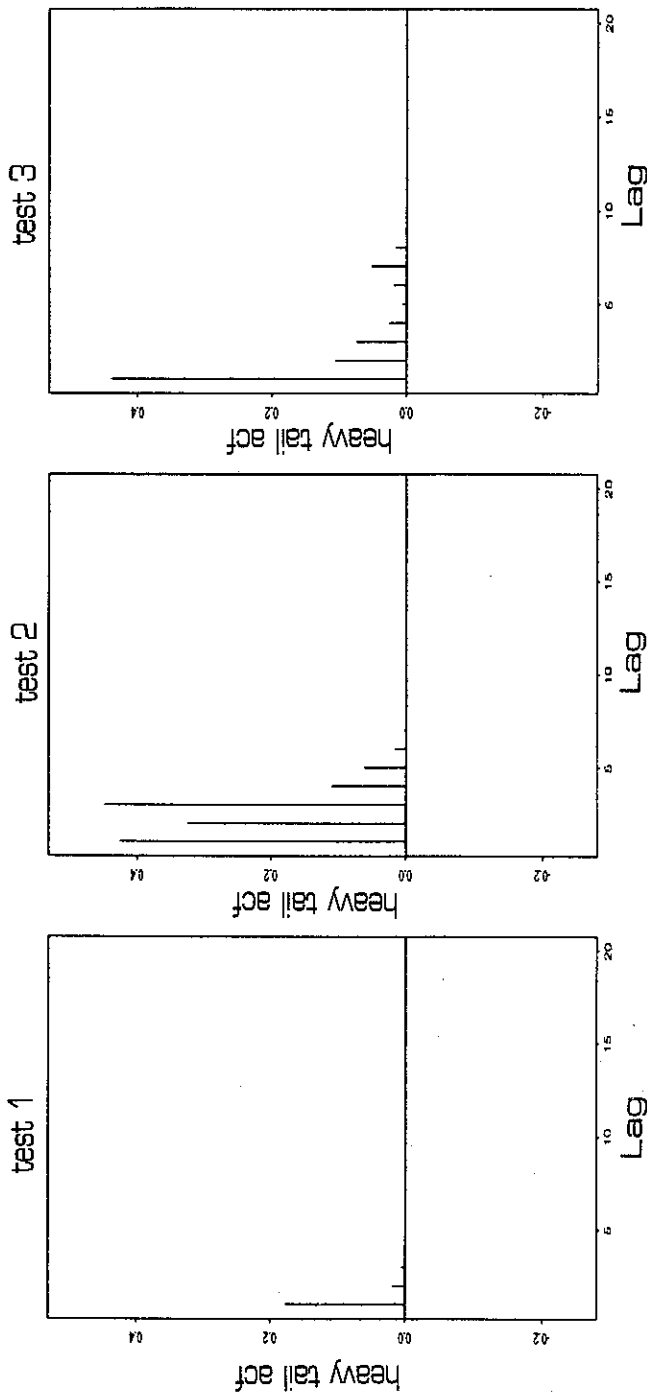


Figure 1: ACF of three independent samples from a bilinear process.

$$X_n = F_{V_n}^{\leftarrow}(U_n)$$

and assume  $\{U_n\}, \{J_n\}, \{D_n^{(i)}, n \geq 0, 1 \leq i \leq p\}$  are all independent.

Thus, changes of state follow the Markov chain  $\{J_n\}$  and a transition from  $i$  to  $j$  occurs with probability  $p_{ij}$ . Having entered state  $i$ , the system stays in state  $i$  for  $k$  time units with probability  $q_k^{(i)}$ . While the  $V$ -process is in state  $i$ , random variables are generated from a distribution  $F_i$ .

One or more of the distributions  $F_i$  may be heavy-tailed. We assume that  $F_1$  has the heaviest tail with index of regular variation  $\alpha$ . Thus

$$\lim_{t \rightarrow \infty} (1 - F_1(tx))/(1 - F_1(t)) = x^{-\alpha} \tag{2.1}$$

and

$$\lim_{t \rightarrow \infty} (1 - F_j(t))/(1 - F_1(t)) = 0, \quad j = 2, \dots, p. \tag{2.2}$$

For a distribution function  $G$ , we will abbreviate the tail function by  $\bar{G} := 1 - G$ .

The above is the definition of a basic hidden semi-Markov model. However, the model, as we have defined it, is not stationary. Note that if  $\{V_n\}$  is stationary, then so is  $\{X_n\}$  since

$$P[X_j \leq x_j, j = 0, \dots, k] = E \left( \prod_{j=0}^k F_{V_j}(x) \right).$$

Since the holding time distributions  $\{q^{(i)}\}$  have finite expectations, it follows that the semi-Markov process  $\{V_n\}$  has a stationary distribution  $\{\nu_i\}$  with

$$\nu_i = \pi_i \tau_i / \sum_{j=1}^p \pi_j \tau_j$$

and where  $\{\nu_i\}$  is also the asymptotic distribution of  $\{V_n\}$ . Since time series modeling is usually done with stationary models we shall modify the definition of the model so that the process  $\{V_n\}$  is stationary and therefore,  $\{X_n\}$  is stationary. This construction can be carried out following the procedure described by Çinlar (1969).

Choose  $V_0$  such that

$$P[V_0 = j] = \nu_j$$

If  $A_{jk}, A'_{jk}$  are the semi-Markov matrices associated with the delayed semi-Markov process  $\{V_n\}$ , following Çinlar (1969), choose

$$A'_{jk}(n) = (1/\tau_j) \sum_{i=0}^n [\tilde{A}_{jk} - A_{jk}(i)]$$

where

$$\tilde{A}_{jk} = A_{jk}(+\infty)$$

In this paper, we shall assume that the underlying semi-Markov process  $\{V_n\}$  is stationary and therefore the hidden semi-Markov model  $\{X_n\}$  is stationary.

### 3 Point process

In this section, we use the asymptotic properties

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so that

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**Lemma 1** Let  $N_n(j)$  time  $n$  so that

Then we have

*Proof.* The proof process  $\{V_j\}$  change

### 3 Point processes associated with the model.

In this section, we use point process techniques to prove a theorem that enables us to study the asymptotic properties of the sample correlation function in the next section.

Let  $\{X_n\}$  be the stationary process defined in Section 2 and define

$$a_n = \inf\{x : \sum_{i=1}^p \nu_i \bar{F}_i(x) \geq n^{-1}\}$$

so that

$$\sum_{i=1}^p \nu_i \bar{F}_i(a_n) \sim \frac{1}{n}.$$

Furthermore we have

$$nP[a_n^{-1}X_1 \in \cdot] \xrightarrow{w} \lambda(\cdot) \tag{3.1}$$

on  $(0, \infty]$  where  $\lambda$  is a measure on  $(0, \infty]$  such that  $\lambda(x, \infty] = x^{-\alpha}$  and the convergence above is in the vague topology on the space of Radon measures on  $(0, \infty]$ . To verify (3.1), use the definition of  $\{X_n\}$  to get

$$\begin{aligned} nP[X_1 > a_n x] &= \sum_{i=1}^p nP[X_1 > a_n x | V_1 = i]P[V_1 = i] \\ &\sim \sum_{i=1}^p \nu_i \bar{F}_i(a_n x) / (\sum_{i=1}^p \nu_i \bar{F}_i(a_n)). \end{aligned}$$

Dividing numerator and denominator by  $\bar{F}_1(a_n)$  and using equations (2.1) and (2.2) we easily see that

$$\lim_{n \rightarrow \infty} nP[X_1 > a_n x] = x^{-\alpha}$$

which suffices for (3.1). □

We need a result about the frequency of visits to each state.

**Lemma 1** *Let  $N_n(j)$  be the number of "visits" to state  $j$  by the semi-Markov chain up to time  $n$  so that*

$$N_n(j) = \sum_{l=1}^n 1_{[V_l=j]}.$$

*Then we have*

$$\lim_{n \rightarrow \infty} N_n^{(j)} / n = \nu_j.$$

*Proof.* The proof is almost exactly as in Resnick and Stărică (1996). The semi-Markov process  $\{V_j\}$  changes states at times  $\{S_n\}$  where

$$S_n = \sum_{q=0}^n D_q^{(J_q)}$$

Let  $\mu_n(j)$  be the number of "visits" to state  $j$  by the underlying Markov chain  $\{J_n\}$ . As  $n \rightarrow \infty$ , we have

$$\begin{aligned} S_n/n &\stackrel{d}{=} (1/n) \sum_{k=1}^p \sum_{i=1}^{\mu_n(k)} D_i^{(k)} \\ &= \sum_{k=1}^p \left[ \sum_{i=1}^{\mu_n(k)} D_i^{(k)} / \mu_n(k) \right] [\mu_n(k)/n] \rightarrow \sum_{k=1}^p E D_1^{(k)} \pi_k \\ &= \sum_{k=1}^p \tau_k \pi_k \end{aligned}$$

Now define the process inverse to  $\{S_n\}$  as

$$M(t) = \sup\{n : S_n \leq t\}$$

so that as  $t \rightarrow \infty$

$$M(t)/t \rightarrow 1 / \left( \sum_{k=1}^p \tau_k \pi_k \right).$$

Note that  $M(t)$  represents the number of changes of state up to time  $t$ . Now

$$\begin{aligned} N_n(k)/n &\leq (1/n) \sum_{q=1}^{M(n)+1} (S_q - S_{q-1}) 1_{[J_{q-1}=k]} \\ &\stackrel{d}{=} (1/n) \sum_{q=0}^{\mu_{(M(n)+1)}(k)} D_q^{(k)} \\ &= \left( \sum_{q=0}^{\mu_{(M(n)+1)}(k)} D_q^{(k)} / \mu_{(M(n)+1)}^{(k)} \right) (\mu_{(M(n)+1)}^{(k)} / (M(n) + 1)) ((M(n) + 1)/n) \\ &\rightarrow \tau_k \pi_k / \sum_{j=1}^p \tau_j \pi_j. \end{aligned}$$

A lower bound is obtained similarly and this completes the proof. □

For what follows, for a nice metric space  $\mathbb{E}$ , we define  $M_p(\mathbb{E})$  to be the Radon point measures on  $\mathbb{E}$ , topologized by the vague topology. A point measure is represented by

$$\sum_i \epsilon_{x_i}$$

where  $x_i \in \mathbb{E}$ . A Poisson process with mean measure  $\lambda$  on  $\mathbb{E}$  will be denoted  $PRM(\lambda)$ .

We now consider point processes based on the observed process  $\{X_n\}$ .

**Proposition 1** *For the stationary process  $\{X_n\}$  defined in Section 2,*

$$\sum_{k=1}^n \epsilon_{a_n^{-1} X_k} \Rightarrow PRM(\lambda)$$

in  $M_p((0, \infty])$ .

*Proof.* We show the convergence in the space of point measures by proving that the corresponding Laplace functionals converge. Therefore, we need to show that for  $f \in C^{\pm}((0, \infty])$

$$\Psi_n(f) = E \exp\{$$

Let  $N_n(j)$  be the number of visits to state  $j$ . Then

$$\Psi_n(f)$$

In the previous Lemma

where  $\{\nu_j\}$  is the stationary distribution

and

Therefore,

$$\prod_{j=1}^p$$

We can now apply the

This completes the proof. Our methods require

for  $k \geq 1$  and fixed  $n$ , the sequence  $\{V_n\}$ .

We now define two

$$\Psi_n(f) = E \exp\left\{-\sum_{j=1}^n f(X_j/a_n)\right\} \rightarrow \exp\left\{-\int_{(0,\infty)} (1 - \exp(-f(x)))\lambda(dx)\right\} \quad (3.2)$$

Let  $N_n(j)$  be the number of "visits" to state  $j$  by the semi-Markov chain up to time  $n$ . Then

$$\begin{aligned} \Psi_n(f) &= E(E(\exp\{-\sum_{j=1}^n f(X_j/a_n)\} | V_0, \dots, V_n)) \\ &= E \prod_{j=1}^p \left( \int_{(0,\infty)} \exp(-f(x)) F_j(a_n dx) \right)^{N_n(j)} \\ &= E \prod_{j=1}^p \left( 1 - \int_{(0,\infty)} \frac{(1 - e^{-f(x)}) n F_j(a_n dx)}{n} \right)^{n \cdot N_n(j)/n} \end{aligned}$$

In the previous Lemma 1, we have shown that

$$\lim_{n \rightarrow \infty} N_n(j)/n = \nu_j$$

where  $\{\nu_j\}$  is the stationary distribution for the semi-Markov chain. For  $j = 2, \dots, p$

$$\lim_{n \rightarrow \infty} n F_j(a_n dx) = 0$$

and

$$\lim_{n \rightarrow \infty} n F_1(a_n dx) = (1/\nu_1)\lambda(dx).$$

Therefore,

$$\begin{aligned} &\prod_{j=1}^p \left( 1 - \int_{(0,\infty)} \frac{(1 - e^{-f(x)}) n F_j(a_n dx)}{n} \right)^{n \cdot N_n(j)/n} \\ &\rightarrow \prod_{j=1}^p \exp\left\{-\int_{(0,\infty)} (1 - e^{-f(x)}) \lim_{n \rightarrow \infty} n F_j(a_n dx) \nu_j\right\} \\ &= \exp\left\{-\int_{(0,\infty)} (1 - \exp(-f(x)))\lambda(dx)\right\}. \end{aligned}$$

We can now apply the dominated convergence theorem to conclude

$$\Psi(f) \rightarrow \exp\left\{-\int_{(0,\infty)} (1 - e^{-f(x)})\lambda(dx)\right\}$$

This completes the proof of the proposition. □

Our methods require the following definition of a new sequence  $\{Y_k\}$ :

$$Y_k = (X_k, \dots, X_{k-m+1})$$

for  $k \geq 1$  and fixed  $m \geq 1$ . The sequence  $\{Y_k\}$  is conditionally  $m$ -dependent given the sequence  $\{V_n\}$ .

We now define two new processes:

$$\begin{aligned} I_n &= \sum_{k=1}^n \epsilon_{a_n^{-1}} Y_k \\ I &= \sum_{k=1}^{\infty} \sum_{i=1}^m \epsilon_{jk} \epsilon_i \end{aligned}$$

where  $\hat{e}_i \in \mathbb{R}^m$  is the basis element with  $i$ th component equal to 1 and the rest equal to zero. Let  $\mathbb{E} = ([0, \infty]^m \setminus \{(0, \dots, 0)\})$ . Let  $\mathcal{S}$  be the collection of all sets  $B$  of the form

$$B = [b_1, c_1] \times \dots \times [b_m, c_m]$$

where  $[b_1, c_1] \times \dots \times [b_m, c_m]$  is bounded away from  $(0, \dots, 0)$ ,  $b_i < c_i$ ,  $b_0 \geq 0$ . It is easy to see that either  $\prod_{i=1}^m [b_i, c_i]$  does not intersect any axis; that is,

$$(C1) \quad [b_1, c_1] \times \dots \times [b_m, c_m] \cap \{y\hat{e}_i : y \in \mathbb{R}_+\} = \emptyset, \text{ for } i = 1, \dots, m$$

or  $\prod_{i=1}^m [b_i, c_i]$  intersects exactly one, say the  $i$ th; that is

$$(C2) \quad [b_1, c_1] \times \dots \times [b_m, c_m] \cap \{y\hat{e}_j : y \in \mathbb{R}_+\} = \begin{cases} [b_i, c_i], & \text{for } j = i, \\ \emptyset, & \text{for } j \neq i. \end{cases}$$

In (C2),  $b_j = 0 < c_j$  and for  $j \neq i$  we have  $b_j > 0$ .

We now give some properties of  $I_n$  and  $I$ .

**Lemma 2** *We have*

$$P[I(\partial B) = 0] = 1$$

for all  $B \in \mathcal{S}$ .

*Proof.* If  $B$  satisfies (C1), the assertion is trivial since  $I$  has all its points on the axes. If  $B$  satisfies (C2),

$$I(\partial B) \leq \sum_{k=1}^{\infty} \epsilon_{j_k}(\{b_i, c_i\}) = 0$$

a.s. since the mean measure of  $\sum_{k=1}^{\infty} \epsilon_{j_k}$  is atomless. □

**Lemma 3** (a) *If  $B \in \mathcal{S}$  satisfies (C1), then*

$$P[I(B) = 0] = 1 \text{ and } EI_n(B) \rightarrow 0.$$

(b) *If  $B \in \mathcal{S}$  satisfies (C2),*

$$P[I(B) = 0] = \exp\{-\lambda([b_i, c_i])\}$$

and

$$E(I_n(B)) \rightarrow \lambda([b_i, c_i]).$$

*Proof.* (a) Let

$$\nu_{i_m, \dots, i_1} = P[V_m = i_m, \dots, V_1 = i_1].$$

We have

$$\begin{aligned} EI_n(B) &= nP(a_n^{-1}X_m \in [b_1, c_1], \dots, a_n^{-1}X_1 \in [b_m, c_m]) \\ &= n \sum_{i_m, \dots, i_1} P(\bigcap_{j=1}^n [a_n^{-1}X_{m-j+1} \in [b_j, c_j]] | V_m = i_m, \dots, V_1 = i_1) \nu_{i_m, \dots, i_1} \\ &= \sum_{i_m, \dots, i_1} F_{i_m}(a_n[b_1, c_1]) \dots F_{i_1}(a_n[b_m, c_m]) \cdot \nu_{i_m, \dots, i_1}. \end{aligned}$$

Since  $B$  has empty interior the above goes to zero

(b) We have

$$EI_n(B) =$$

Since  $b_j = 0 < c_j$

and so

This completes the proof

**Proposition 2** *Let*

for all  $B \in \mathcal{S}$ .

*Proof.* We can assume  $B$  satisfies (C1),  $EI_n(B) \rightarrow 0$ . Suppose  $B$  satisfies

By stationarity of the process  $(i-1).P[a_n^{-1}X_1 \in [b_i, c_i]]$

and it suffices to show

The second term,  $I_n(B)$

Also

and the rest equal to sets  $B$  of the form

$b_0 \geq 0$ . It is easy to

$\dots, m$

$j = i,$   
 $j \neq i.$

points on the axes.

□

Since  $B$  has empty intersection with the coordinate axes and the inner summation is finite, the above goes to zero as  $n \rightarrow \infty$ .

(b) We have

$$\begin{aligned} EI_n(B) &= nP[a_n^{-1}X_k \in [b_1, c_1], \dots, a_n^{-1}X_{k-m+1} \in [b_m, c_m]] \\ &= nP\left(\prod_{i=1}^n [a_n^{-1}X_{m-l+1} \in [b_l, c_l] | V_m = i_m, \dots, V_1 = i_1\right) \nu_{i_m, \dots, i_1} \\ &= \sum_{i_m, \dots, i_1} F_{i_m}(a_n[b_1, c_1]) \dots F_{i_1}(a_n[b_m, c_m]) \cdot \nu_{i_m, \dots, i_1}. \end{aligned}$$

Since  $b_j = 0 < c_j$  for  $j \neq i$ ,  $F_{i_j}(a_n[b_j, c_j]) \rightarrow 1$  as  $n \rightarrow \infty$  for  $j \neq i$ . Therefore,

$$E(I_n(B)) \sim P[V_1 = 1]F_1(a_n[b_i, c_i]) / (\nu_1 F_1(a_n))$$

and so

$$E(I_n(B)) \rightarrow \lambda[b_i, c_i]$$

This completes the proof of the lemma. □

**Proposition 2** Let  $\tilde{I}_n = \sum_{k=1}^n \sum_{i=1}^m \epsilon_{(a_n^{-1}Y_k, \delta_i)}$ . Then

$$I_n(B) - \tilde{I}_n(B) \xrightarrow{P} 0$$

for all  $B \in \mathcal{S}$ .

*Proof.* We can assume, without loss of generality, that  $B = [b_1, c_1] \times \dots \times [b_m, c_m]$ . If  $B$  satisfies (C1),  $EI_n(B) \rightarrow 0$  and  $\tilde{I}_n(B) = 0$  which proves the result in this case.

Suppose  $B$  satisfies (C2). Then  $b_j = 0$  for  $j \neq i$  and  $b_i > 0$ . Write

$$I_n(B) = \sum_{k=1}^{i-1} \epsilon_{(a_n^{-1}Y_k)}(B) + \sum_{k=i}^n \epsilon_{(a_n^{-1}Y_k)}(B). \tag{3.3}$$

By stationarity of the process  $\{X_n\}$ , the expectation of the first term is bounded above by  $(i-1) \cdot P[a_n^{-1}X_1 \in [b_i, c_i]]$  which tends to zero as  $n \rightarrow \infty$  since  $b_i > 0$ . This expresses

$$I_n(B) = o_p(1) + I_n^{(1)}(B)$$

and it suffices to show

$$I_n^{(1)}(B) - \tilde{I}_n(B) \xrightarrow{P} 0. \tag{3.4}$$

The second term,  $I_n^{(1)}(B)$  in (3.3) can be bounded above by

$$\sum_{j=1}^{n-i+1} \epsilon_{(a_n^{-1}X_j)}([b_i, c_i]) \leq \sum_{j=1}^n \epsilon_{a_n^{-1}X_j}([b_i, c_i]) = \tilde{I}_n(B).$$

Also

$$E\tilde{I}_n(B) = \sum_{j=1}^n P[a_n^{-1}X_j \in [b_i, c_i]]$$

$V_1 = i_1) \nu_{i_m, \dots, i_1}$

$$= nP(a_n^{-1}X_1 \in [b_i, c_i]) \rightarrow \lambda([b_i, c_i])$$

from (3.1). We thus conclude that

$$0 \leq \tilde{I}_n(B) - I_n(B) \xrightarrow{L_1} 0$$

and therefore,

$$\tilde{I}_n(B) - I_n^{(1)}(B) \xrightarrow{P} 0$$

as required. This completes the proof of the proposition.  $\square$

**Proposition 3** *We have*

$$\sum_{k=1}^n \epsilon_{(a_n^{-1}Y_k)} \Rightarrow \sum_{k=1}^{\infty} \sum_{i=1}^m \epsilon_{(j_k \epsilon_i)}$$

in  $M_p(\mathbb{E})$ , where  $\mathbb{E} := [0, \infty]^m \setminus \{0\}$  and  $\{(j_k) : k \geq 1\}$  are the points of a PRM( $\lambda$ ) on  $(0, \infty]$ .

*Proof.* By the result of the previous Proposition 2, it clearly suffices to show that

$$\tilde{I}_n = \sum_{k=1}^n \sum_{i=1}^m \epsilon_{a_n^{-1}Y_k \cdot \epsilon_i} \Rightarrow \sum_{k=1}^{\infty} \sum_{i=1}^m \epsilon_{j_k \epsilon_i}$$

By the result of Lemma 2

$$\sum_{k=1}^n \epsilon_{a_n^{-1}X_k} \Rightarrow \sum_{k=1}^{\infty} \epsilon_{j_k}$$

in  $M_p((0, \infty])$ . Further, the mapping

$$\epsilon_{v_k} \mapsto \left( \sum_{k=1}^{\infty} \epsilon_{v_k \cdot \epsilon_1}, \dots, \sum_{k=1}^{\infty} \epsilon_{v_k \cdot \epsilon_m} \right) \mapsto \sum_{k=1}^{\infty} \sum_{i=1}^m \epsilon_{v_k \cdot \epsilon_i}$$

is continuous from  $M_p((0, \infty])$  into  $M_p(\mathbb{E})$ . By the continuous mapping theorem, it follows that

$$\tilde{I}_n \Rightarrow \sum_{k=1}^{\infty} \sum_{i=1}^m \epsilon_{(j_k \cdot \epsilon_i)}$$

This completes the proof of the proposition.  $\square$

### 4 Asymptotic properties of sample correlation function.

This section concentrates on describing the asymptotic behavior of the sample autocorrelation function (acf) for the heavy tailed hidden Markov model. The classical sample acf is defined in time series analysis as

In heavy tail analysis, the main point is to center the distribution.

See Davis and Resnick (1998). From the Proposition 3, we have

Let  $\gamma > 0$ , and for  $h > 0$

by

The map  $\Phi_{h,\gamma}$  is a.s. continuous map

$$\left( \Phi_{h,\gamma} \left( \sum_{k=1}^n \epsilon_{v_k} \right) \right)$$

converges in distribution

where  $(j_k^2, k \geq 1)$  are the points of a PRM( $\lambda$ ) on  $(0, \infty]$ . As  $\gamma \rightarrow 0$ , the limit is  $h > 0$ .

**Lemma 4** For any  $h > 0$

*Proof.* The proof is

By the Cauchy-Schwarz inequality

$$\hat{\rho}(h) = \frac{\sum_{t=1}^{n-h} (X_t - \bar{X})(X_{t+h} - \bar{X})}{\sum_{t=1}^n X_t^2}, \quad h = 0, 1, \dots$$

In heavy tail analysis where neither variances nor means are guaranteed to exist, there is little point to centering by means of  $\bar{X}$  and so we define

$$\hat{\rho}_H(h) = \frac{\sum_{t=1}^{n-h} X_t X_{t+h}}{\sum_{t=1}^n X_t^2}, \quad h = 0, 1, \dots$$

See Davis and Resnick (1985, 1986)

From the Proposition 3, we have

$$\sum_{k=1}^n \epsilon_{a_n^{-1} Y_k} \Rightarrow \sum_{k=1}^{\infty} \sum_{i=1}^m \epsilon_{j_k \cdot \epsilon_i} \tag{4.1}$$

Let  $\gamma > 0$ , and for each integer  $h, 0 \leq h \leq m - 1$ , define the mapping

$$\Phi_{h,\gamma} : M_p(\mathbb{E}) \mapsto \mathbb{R}_+$$

by

$$\Phi_{h,\gamma} \left( \sum_{k=1}^{\infty} \epsilon_{(u_{k,0}, \dots, u_{k,m-1})} \right) = \sum_{k=1}^{\infty} u_{k,0} u_{k,h} \mathbf{1}_{[|u_{k,0}| > \gamma \text{ or } |u_{k,h}| > \gamma]} \tag{4.2}$$

The map  $\Phi_{h,\gamma}$  is a.s. continuous relative to the limit point process in (4.1). Therefore, by the continuous mapping theorem,

$$\begin{aligned} & \left( \Phi_{h,\gamma} \left( \sum_{k=1}^n \epsilon_{a_n^{-1} (X_k, \dots, X_{k-m+1})} \right), h = 0, \dots, m - 1 \right) \\ &= \left( a_n^{-2} \sum_{k=1}^n X_k X_{k-h} \mathbf{1}_{[|X_k| > a_n \gamma \text{ or } |X_{k-h}| > a_n \gamma]}, h = 0, 1, \dots, m - 1 \right) \end{aligned}$$

converges in distribution in  $[0, \infty]^m$  to the random variable whose components are

$$\Phi_{h,\gamma} \left( \sum_{k=1}^{\infty} \sum_{i=1}^m \epsilon_{j_k \cdot \epsilon_i} \right) = \begin{cases} 0, & \text{for } h > 0, \\ \sum_{k=1}^{\infty} j_k^2 \mathbf{1}_{[|j_k| > \gamma]}, & \text{for } h = 0, \end{cases}$$

where  $(j_k^2, k \geq 1)$  are the points of a PRM( $\tilde{\lambda}$ ) on  $(0, \infty]$  with  $\tilde{\lambda}(dx) = x^{-\alpha/2-1}(\alpha/2)dx$ .

As  $\gamma \rightarrow 0$ , the limit random variable approaches  $\sum_{k=1}^{\infty} j_k^2$  for  $h = 0$  and equals zero for  $h > 0$ .

**Lemma 4** For any  $\eta > 0$ , if  $0 < \alpha < 2$ , then

$$\lim_{\gamma \rightarrow 0} \limsup_{n \rightarrow \infty} P[a_n^{-2} \left| \sum_{k=1}^n X_k X_{k-h} \mathbf{1}_{[|X_k| \leq a_n \gamma, |X_{k-h}| \leq a_n \gamma]} \right| > \eta] = 0$$

*Proof.* The probability in the hypothesis of the lemma is bounded above by

$$(n/(a_n^2 \eta)) E[|X_k| \mathbf{1}_{[|X_k| \leq a_n \gamma]} |X_{k-h}| \mathbf{1}_{[|X_{k-h}| \leq a_n \gamma]}]$$

By the Cauchy-Schwartz inequality, the above has an upper bound

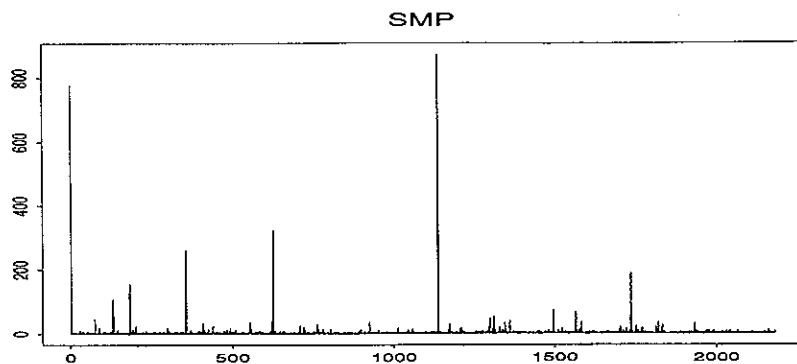


Figure 2: Time series plot.

$$(n/(a_n^2 \eta)) [EX_k^2 1_{[|X_k| \leq a_n \eta]}]^{1/2} [EX_{k-l}^2 1_{[|X_{k-l}| \leq a_n \eta]}]^{1/2}$$

By stationarity, the above equals  $(n/(a_n^2 \eta)) EX_1^2 1_{[|X_1| \leq a_n \eta]}$ . From (3.1),  $X_1$  has regularly varying tail probabilities. If  $0 < \alpha < 2$ , the result follows from Karamata's Theorem.  $\square$

Now for the result about the sample acf.

**Proposition 4** Assume  $0 < \alpha < 2$ . Then we have

$$(\hat{\rho}_H(l), l = 1, \dots, m) = \left( \frac{\sum_{t=1}^{n-l} X_t X_{t+1}}{\sum_{t=1}^n X_t^2}, l = 1, \dots, m \right) \Rightarrow (0, \dots, 0).$$

Thus the sample correlation function at nonzero lags is asymptotically equal to zero. This is the same behavior exhibited by the sample acf of heavy tailed iid sequences.

*Proof.* Using the result of the previous Lemma 4, we can apply Theorem 4.2 in Billingsley (1968) to conclude that

$$a_n^{-2} \left( \sum_{t=1}^n X_t^2, \sum_{t=1}^n X_t X_{t-1}, \dots, \sum_{t=1}^n X_t X_{t-m+1} \right) \Rightarrow \left( \sum_{k=1}^{\infty} j_k^2, 0, \dots, 0 \right).$$

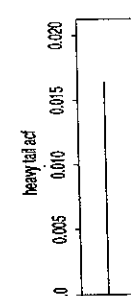
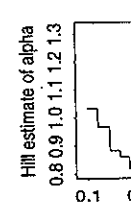
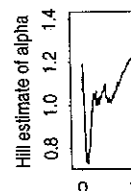
Again, by the continuous mapping theorem, it follows that

$$\left( \frac{\sum_{t=1}^n X_t X_{t-1}}{\sum_{t=1}^n X_t^2}, \dots, \frac{\sum_{t=1}^n X_t X_{t-m+1}}{\sum_{t=1}^n X_t^2} \right) \Rightarrow (0, \dots, 0).$$

This completes the proof of the proposition.  $\square$

### 5 Concluding remarks.

To illustrate the results, we simulated a five state semi-Markov process with transition matrix



The holding times 1.5, 1.6, 1.7 and t. The realization of SMP. The time se

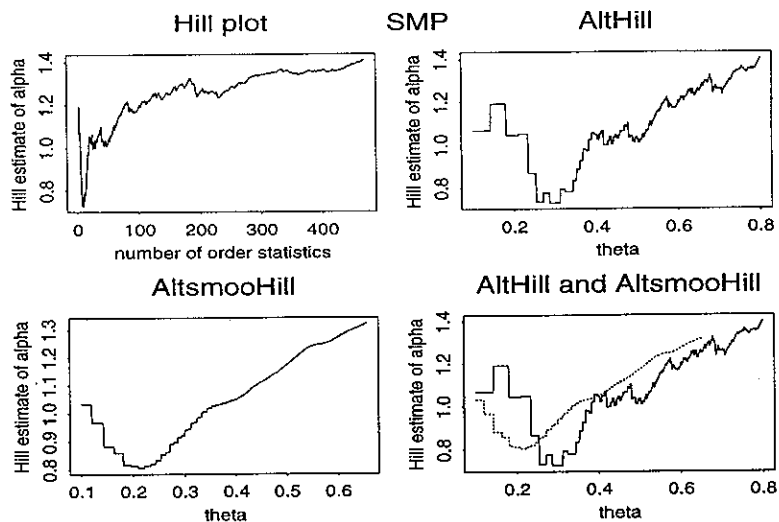


Figure 3: Hill plot.

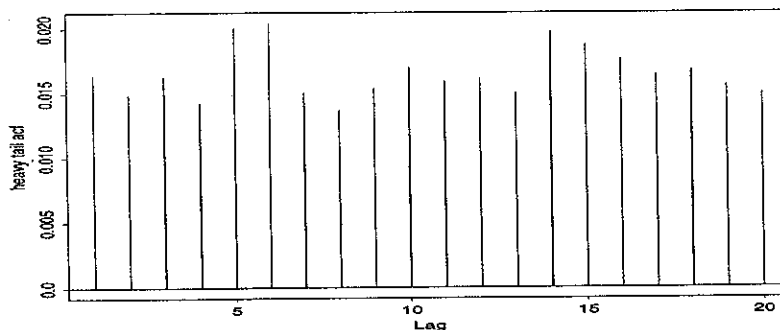


Figure 4: ACF plot of SMP.

$$P = \begin{pmatrix} 0.0 & 0.2 & 0.3 & 0.2 & 0.3 \\ 0.4 & 0.0 & 0.2 & 0.3 & 0.1 \\ 0.3 & 0.1 & 0.0 & 0.4 & 0.2 \\ 0.1 & 0.2 & 0.2 & 0.0 & 0.5 \\ 0.4 & 0.1 & 0.2 & 0.1 & 0.2 \end{pmatrix}$$

The holding times in each state have discrete Pareto distributions with exponents 1.3, 1.4, 1.5, 1.6, 1.7 and the  $F_i$ 's were Pareto distributions with parameters 0.7, 0.9, 1.3, 1.5, 1.8. The realization of the resulting time series  $\{X_n, n \geq 1\}$  is of length 2182 and is labeled SMP. The time series plot of SMP is given in Figure 2.

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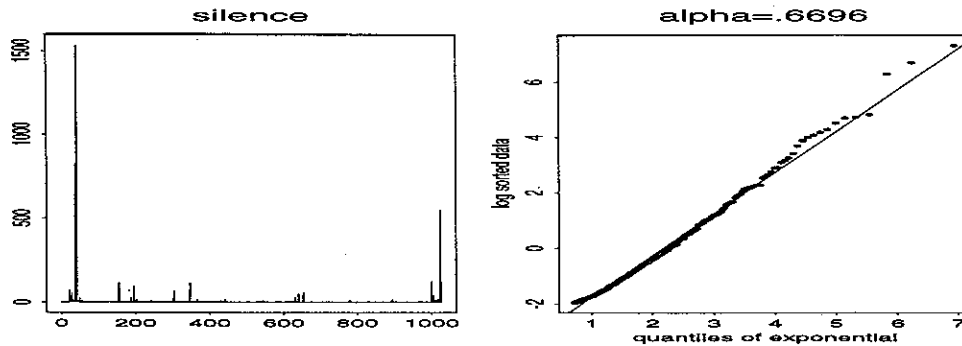


Figure 5: Tsplo and static qq-plot of SILENCE.

A popular estimator of tail heaviness is the Hill estimator and we were curious to see how this estimator performed on our data. Usually the Hill estimator is quite accurate for Pareto data and the question arose: How accurate would it be for data produced by the mixture method induced by the semi-Markov process. The results are satisfactory although one must push the Hill estimator using smoothing and alternate plotting. The Hill estimator is obtained by first computing the order statistics of the data

$$X_{(1)} \geq X_{(2)} > \cdots > X_{(n)}$$

and defining

$$H_{k,n} = \frac{1}{k} \sum_{i=1}^k \log \left( \frac{X_{(i)}}{X_{(k+1)}} \right)$$

where  $k$  is the number of order statistics used in estimation. The estimate of  $\alpha$  is  $H_{k,n}^{-1}$ . The way estimation is done in practice is to make a *Hill plot* of  $\{(k, H_{k,n}^{-1}), 1 \leq k \leq n\}$ . Resnick and Stărică (1997) recommend using a supplementary plot, called the *alt-plot*, where one plots

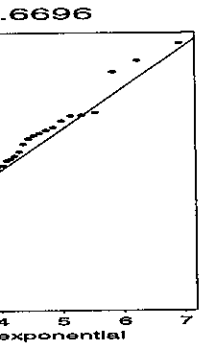
$$\{(\theta, H_{[n^\theta],n}^{-1}), 0 \leq \theta \leq 1\}$$

and also *smoothing*. The Hill plot is given in four views in Figure 3. Considering the correct answer is 0.7, the ordinary Hill plot is not overly revealing. However, the alt plot and the smoothed alt plot come quite close to the known value of 0.7.

Figure 4 gives the sample acf of the simulated data. The values for 20 lags are quite small, with the biggest being 0.0204. Note the vertical scale extends from 0 to 0.02.

Next, consider a time series, called SILENCE, of length 1027 shown in Figure 5 which represents the off periods between transmission of packets generated by a terminal during a session. The left graph in Figure 5 is the time series plot and the right graph is the static qq-plot using 500 upper order statistics giving ample evidence of heavy tails. The estimate of  $\alpha$  given by this plot is 0.6696 and the Hill estimator (not shown) gives  $\hat{\alpha} \approx .64$  so that for this distribution the mean is infinite.

For the last graph, we split the data set into thirds and graphed the acf for each piece separately. The pictures are obviously quite different. The strong suspicion is that if this



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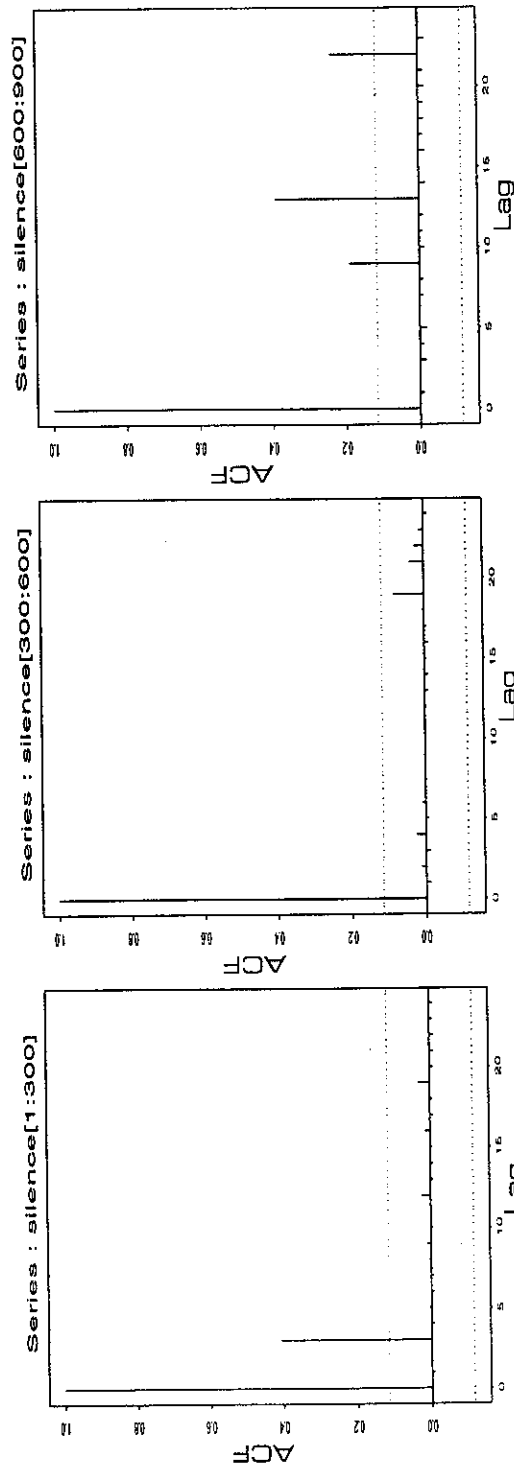


Figure 6: Acf plots of SILENCE.

data could be modeled by a hidden Markov model, the acf pictures would look almost identical so we have rejected the hidden Markov model as a candidate.

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## LÉVY

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## 1 Lévy Pr

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where  $\phi(\theta) = E\{e^{i\theta X(t)}\}$ . The following theorem states that a Lévy process is a divisible distribution.

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