

Parameter Estimation of a Mixture Distribution

Let X_1, \dots, X_n be a stationary time series with extremal index $\theta \in (0, 1]$ (see Beirlant et al, 2004) and W_1, \dots, W_n iid, heavy-tailed waiting times. We can show that the limiting distribution of the excess waiting times with threshold u_n ($u_n \rightarrow x_R$) is a mixture distribution out of the dirac measure at point zero and the Mittag-Leffler distribution $ML(\beta, \theta^{-1/\beta})$, $\beta \in (0, 1]$, with weights $(1 - \theta, \theta)$:

$$\mathbb{P}_{\beta, \theta} := (1 - \theta)\delta_0 + \theta \cdot ML(\beta, \theta^{-1/\beta}). \quad (1)$$

We want to estimate the two unknown parameters β and θ with the method of moments. But since the ML-distribution does not have finite moments we have a look at the fractional moments. Let $q \in (0, 1)$. The q -th fractional moment of a $ML(\beta, \gamma)$ -distributed random variable Y is:

$$\mathbb{E}(Y^q) = \frac{q \cdot \pi \cdot \gamma^q}{\beta \cdot \Gamma(1 - q) \sin(\frac{q \cdot \pi}{\beta})}, \quad \text{for } 0 < q < \beta \quad (2)$$

(Cahoy, 2013). Then the q -th fractional moment of $T \sim \mathbb{P}_{\beta, \theta}$ is

$$\begin{aligned} m_q := m_q(T) &:= \mathbb{E}(T^q) = (1 - \theta)\mathbb{E}(Y^q) + \theta\mathbb{E}(X^q) = \theta\mathbb{E}(X^q) \\ &= \theta^{\frac{\beta-q}{\beta}} \cdot \frac{q \cdot \pi}{\beta \cdot \Gamma(1 - q) \sin(\frac{q \cdot \pi}{\beta})} \end{aligned} \quad (3)$$

with $Y \sim \delta_0$ and $X \sim ML(\beta, \theta^{-1/\beta})$, $q < \beta$. The empirical q -th fractional moment $\hat{m}_q = \frac{1}{n} \sum_{i=1}^n T_i^q$, $T_1, \dots, T_n \stackrel{iid}{\sim} \mathbb{P}_{\beta, \theta}$, is an unbiased estimator of m_q and for $2q < \beta$ the estimator \hat{m}_q is consistent in mean square:

$$\begin{aligned} \text{Var}(\hat{m}_q) &= \mathbb{E}(\hat{m}_q^2) - \mathbb{E}(\hat{m}_q)^2 \\ &= \frac{1}{n^2} \mathbb{E} \left(\sum_{i \neq j} T_i^q T_j^q + \sum_{i=1}^n T_i^{2q} \right) - m_q^2 \\ &= \frac{1}{n^2} \left(n(n-1)\mathbb{E}(T_1^q)^2 + n\mathbb{E}(T_1^{2q}) \right) - m_q^2 \\ &= \frac{n-1}{n} m_q^2 + \frac{1}{n} m_{2q} - m_q^2 \xrightarrow{n \rightarrow \infty} 0. \end{aligned} \quad (4)$$

Since $\lim_{x \rightarrow 0} \frac{\sin(x\pi)}{x\pi} = 1$ (easily shown by using L'Hopital's rule) and $\Gamma(1) = 1$ it follows

$$\lim_{q \rightarrow 0} m_q = \theta. \quad (5)$$

By solving (??) for θ and using the empirical fractional moment \hat{m}_q , we get an estimator $\hat{\theta}_q(\beta)$ depending on β :

$$\hat{\theta}_q(\beta) = \left[\frac{\beta \cdot \Gamma(1 - q) \sin(\frac{q \cdot \pi}{\beta})}{q \cdot \pi} \cdot \hat{m}_q \right]^{\frac{\beta}{\beta - q}} \quad (6)$$

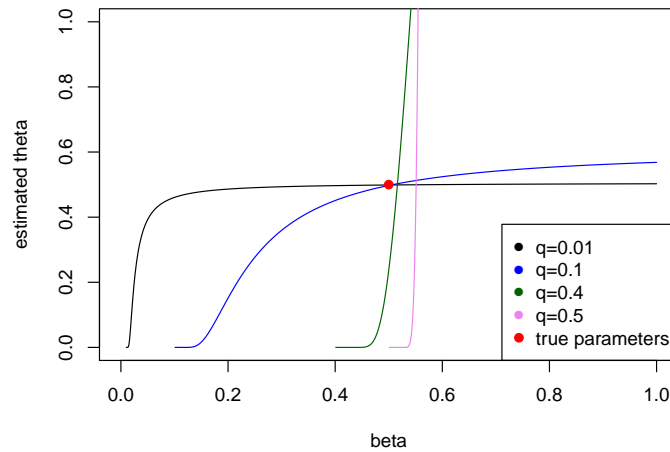


Figure 1: Figure 1 shows $\hat{\theta}_q(\beta)$ depending on β for various fractions q . It is based on $n = 10000$ $\mathbb{P}_{0.5,0.5}$ -distributed data.

Therefore we have to estimate β first by calculating the root of $\hat{\theta}_{q_1}(\beta) - \hat{\theta}_{q_2}(\beta)$ on $(\max(q_1, q_2), 1]$ (we choose $\max(q_1, q_2)$ as the lower interval limit because $\beta > q_1, q_2$ has to be fulfilled, otherwise the fractional moments don't exist). It is important to choose the fractions q_1 and q_2 small enough (smaller than the (unknown) β) otherwise we can't find β by calculating the root of $\hat{\theta}_{q_1}(\beta) - \hat{\theta}_{q_2}(\beta)$ because $\beta \notin (\max(q_1, q_2), 1]$ for $\beta \leq q_1, q_2$. $\hat{\theta}_q(\beta)$ is not unbiased but for smaller q the bias gets smaller because of (??).

Figure ?? shows $\hat{\theta}_q(\beta)$ depending on β for various fractions q . We can see that the curves of lower fractions q intersect the true parameter while the curve of $p = 0.5 = \beta$ doesn't. As well we can see that for small fraction q the estimator $\hat{\theta}_q(\beta)$ is less dependent of β .

Now we look how it works with R:

```
set.seed(2345)

## chosen parameters:
# 1) true parameters
beta <- 0.5
theta <- 0.5

# 2) random sample
n <- 10000                                # sample size

# 3) fractions
q1 <- 0.01
q2 <- 0.05

## sample:
prob <- sample( c(0,1) , size = n , replace = T , prob = c(1-theta , theta))
```

```

# we need the R-package 'MittagLeffler' to sample ML-distributed values:
# install.packages("MittagLeffler")

daten <- sapply(prob ,                               # sample
  function(x){ ifelse( x == 0 , return(0) ,
    return( MittagLeffler::rml(1 , tail = beta ,
      scale = theta^(-1/beta))
    ) ) } )

## functions:
fct_empfracmom <- function( q , data ){               # emp. frac. moment
  r <- 1/(length(data))*sum(data^q)
  return(r) }

fct_theta <- function( beta , q , data ){             # estimator for theta
  r <- ( ( beta*gamma(1-q)*sin(pi*q/beta) )/( q*pi ) *
    fct_empfracmom(q , data) )^(beta/(beta-q))
  return(r) }

fct_root <- function( beta , q1 , q2 , data ){
  r <- fct_theta( beta , q1 , data) - fct_theta( beta , q2 , data)
  return(r) }

fct_beta <- function(q1 , q2 , data ){                # estimator for beta
  r <- uniroot(fct_root , c(max(q1,q2)+0.001,1) , q1 = q1 ,
    q2 = q2 , data = data)
  return(r$root) }

## estimating beta and theta
# estimating beta by calculating the root:
beta_hat1 <- fct_beta(q1=q1 , q2=q2 , data = daten); beta_hat1

## [1] 0.4992572

# estimating theta by using beta_hat1
theta_hat11 <- fct_theta(beta = beta_hat1 , q=q1 , data = daten); theta_hat11

## [1] 0.5020829

theta_hat12 <- fct_theta(beta = beta_hat1 , q=q2 , data = daten); theta_hat12

## [1] 0.5020837

```

```

# error:
abs(beta-beta_hat1); abs(theta-theta_hat11); abs(theta-theta_hat12)

## [1] 0.0007427727
## [1] 0.00208289
## [1] 0.002083718

## -> it works

# estimating theta by calculating the q-th emp. frac. moment with q very small:
theta_hat2 <- fct_empfracmom(10^{-6} , data=daten); theta_hat2

## [1] 0.5021004

beta_hat2 <- uniroot(function(x){fct_theta(x , q=q1 , data=daten)-theta_hat2} ,
interval = c(q1,1))$root; beta_hat2

## [1] 0.5003904

abs(beta-beta_hat2); abs(theta-theta_hat2)

## [1] 0.0003903841
## [1] 0.002100401

## -> works as well;
## -> unsolved problem: which fraction q is small enough
## to estimate theta reliably?

```