Computational details for ppstat

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1 The likelihood and derivatives

The core computational problem in the use of point processes for statistical modeling is the optimization of the minus-log-likelihood function, which is given as

$$l(\theta) = \int_0^T \lambda_\theta(s)\mathrm{d}s - \sum_{j=1}^{n} \log \lambda_\theta(t_j)$$

where $0 < t_1 < t_2 < \ldots < t_n < T$ are observations and λ_θ is a parameterized family of intensities. Typically $\theta \in \Theta \subseteq \mathbb{R}^p$. For the Hawkes family of generalized linear point process models in `ppstat` we consider situations where

$$\lambda_\theta(t) = \phi\left(\alpha^T X(t) + \sum_{m=1}^{K} \sum_{i=1}^{n(m)} h^m_{\beta^m}(t - s_i^m)\right)$$

where $\phi : I \to [0, \infty)$, $I \subseteq \mathbb{R}$, is a given function,

$$\theta = \begin{pmatrix} \alpha \\ \beta^1 \\ \vdots \\ \beta^K \end{pmatrix}$$

and $s_1^m < \ldots < s^m_{n(m)} < t$ for $m = 1, \ldots, K$ are observations of point processes (one of these sets of points could be the t_i observations above). The process $X(t)$ is an auxiliary, $d(0)$-dimensional observed processes – observed at least discretely. The processes

$$\sum_{i=1}^{n(m)} h^m_{\beta^m}(t - s_i^m)$$

are linear filters using the (parameterized) filter function $h^m_{\beta^m}$, which are given via a basis expansion

$$h^m_{\beta^m}(t) = (\beta^m)^T B(t) = \sum_{l=1}^{d(m)} \beta_l^m B_l(t),$$

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and $\beta^m \in \mathbb{R}^{d(m)}$. Collecting these ingredients – and interchanging two sums – the intensity function can be written as

$$\lambda_\theta(t) \quad = \quad \phi\left(\alpha^T X(t) + \sum_{m=1}^{K} \sum_{l=1}^{d(m)} \beta_l^m \sum_{i=1}^{n(m)} B_l(t - s_i^m)\right) = \phi\left(\theta^T Z(t)\right)$$

with $Z(t)$ a process of dimension $p = d(0) + d(1) + \ldots + d(K)$. Each of the linear filter components

$$\sum_{i=1}^{n(m)} B_l(t - s_i^m)$$

are computable from the observations and the fixed choice of basis. The minus-log-likelihood function that we want to minimize reads

$$l(\theta) = \int_0^T \phi\left(\theta^T Z(s)\right) \mathrm{d}s - \sum_{j=1}^{n} \log \phi\left(\theta^T Z(t_j)\right).$$

The integral is not in general analytically computable. We discretize time to have a total of N time points and let Z denote the $N \times p$ matrix of the $Z(t)$-process values at the discretization points. With Δ the N-dimensional vector of interdistances from the discretization we arrive at the approximation of the minus-log-likelihood function that we seek to minimize:

$$l(\theta) \simeq \Delta^T \phi\left(Z\theta\right) - \sum_{j=1}^{n} \log \phi\left(\theta^T Z(t_j)\right).$$

We have used the convention that ϕ applied to a vector means coordinate-wise applications of ϕ. Using this expression a precomputation of the Z matrix will allow for a rapid computation of (the approximation to) l. The derivatives are likewise approximated as

$$Dl(\theta) \simeq \left[\Delta \circ \phi'\left(Z\theta\right)\right]^T Z - \sum_{j=1}^{n} \frac{\phi'\left(\theta^T Z(t_j)\right)}{\phi\left(\theta^T Z(t_j)\right)} Z(t_j)^T$$

with $\circ$ the Hadamard (or coordinate-wise) matrix product and

$$D^2 l(\theta) \simeq Z^T[\Delta \circ \phi''\left(\theta^T Z\right) \circ Z] - \sum_{j=1}^{n} \frac{\phi''\left(\theta^T Z(t_j)\right)\phi\left(\theta^T Z(t_j)\right) - \phi'\left(\theta^T Z(t_j)\right)^2}{\phi\left(\theta^T Z(t_j)\right)^2} Z(t_j) Z(t_j)^T.$$

2 Algorithms for optimization

The BFGS and L-BFGS-B algorithms as implemented in R.

The iterative weighted least squares algorithm.