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Dictionary learning for M/EEG multidimensional data

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Introduction

Signals obtained from magneto- or electroencephalography (M/EEG) are very noisy and inherently multi-dimensional, i.e. provide a vector of measurements at each single time instant. To cope with noise, researchers traditionally acquire measurements over multiple repetitions (trials) and average them to classify different patterns of activity. This is not optimal because of trial-to-trial variability (waveform variation, jitters). The jitter-adaptive dictionary learning method (JADL) has been developed to better handle this variability (with a particular emphasis on jitters). JADL is a data-driven method that learns a dictionary (prototype pieces) from a set of signals, but is currently limited to a single channel, which restricts its capacity to work with very noisy data such as M/EEG. We propose an extension to the jitter-adaptive dictionary learning method, that is able to handle multidimensional measurements such as M/EEG.

1. Jitter-adaptive dictionary learning model (JADL)

JADL is a dictionary learning framework

- Atoms learned by JADL are defined on the entire signal domain.
- Assumptions:
  - The set of signals {s}(t) can be generated by a dictionary.
  - Each atom is shifted version of the learned atom, with shifts \( \Delta \) of all its atoms.

The algorithm solving the JADL problem, is based on an implementation in [2] for common dictionary learning, which iteratively alternates between:

(i) Sparse coding: finding the coefficients \( \{ a_i \} \) and the jitters \( \{ \Delta_i \} \)

Let an "uncoupled" version of the dictionary \( D \) be a dictionary \( D^0 \) containing all allowed shifts (\( S = \{ \Delta \} \)) of all its atoms:

\[
D^0 = \{ d_i \} \in \mathbb{R}^{N 	imes KS},
\]

where \( s_i \) is a shifted version of the learned atom, and \( d_i \) is a generated atom, \( a_i \) is a learned atom and \( a_i + \delta \) is a shifted version of the learned atom, with shifts \( \Delta_{ij} \) within the expected range \( \Delta = \{ \Delta_i \} \)

The dictionary update problem (ii) is also slightly modified to treat the measurements corresponding to the different channels as additional trials.

2. Our modified JADL model

We propose an extension to the jitter-adaptive dictionary learning method, that:

- Is able to handle multidimensional measurements such as M/EEG.
- Learn a dictionary over M/EEG recordings that have the same waveform and jitter over all the channels in a single trial.
- Is still able to account for different jitters across trials.

Significant modifications are applied to the original JADL framework, especially in:

The solution of sparse coding problem (ii) by least angle regression algorithm (LARS):

1. Atom Selection: The best shifted versions of the atoms contained in the extended dictionary \( D^0 \) are selected, over all the channels, leading to a compressed dictionary \( D_{c} \).

   \[
   d_{c}^i = \arg \min_{d_j} \| s_i - d_j \|_2 \quad \text{subject to} \quad \| a_i \|_1 \leq 1, \quad 1 \leq i \leq K
   \]

   where \( C \) is the number of channels of the EEG data, \( s_i \) is the signal of channel \( c \) and \( d_{c}^i \) is the \( j \)-th atom of the extended dictionary \( D^0 \).

2. Standard LARS sparse coding over the channels for the current atom set. During this step the multi-dimensional coefficients \( a_{ji} \) are computed using the compressed dictionary \( D_{c} \) selected by the previous step and the multi-channel signals for the given trials.

The dictionary update problem (ii) is slightly modified to treat the measurements corresponding to the different channels as additional trials.

3. Synthetic data generation

- Create a dictionary \( K = 3 \) synthetic atoms.
- Generate an extended dictionary of 9 signals:
  - Introducing random jitters (from the set \( \Delta = \{ s | s > 100 \text{ contiguous allowed shifts} \} \)) to the dictionary's atoms.
  - Select 3 source groups, each of them containing 3 neighboring sources.
  - Each source group is associated to shifted versions of the same atom.
  - Combine the generated signals with a lead field matrix \( G \) computed from real EEG measurements [3].

   \[
   G = \mathbf{F} \mathbf{S}
   \]

   where \( \mathbf{F} \in \mathbb{R}^{101 \times 101} \) is the measurement matrix either EEG or MEG, \( \mathbf{C} \in \mathbb{R}^{101 \times 101} \) is the lead field matrix. \( \mathbf{C} \) and \( \mathbf{S} \) are the numbers of channels, sources and time samples respectively.
  - Perform the above procedure for \( M \) trials.
  - Introducing new random jitters to the dictionary of \( K = 3 \) synthetic atoms.
  - Generated clean M/EEG measurements of \( C = 6 \) channels, \( M = 200 \) trials and \( N = 515 \) time samples.

4. Results on lead field synthetic data

A comparison between the original and our multi-dimensional JADL model

Both algorithms are executed with the same signals, initial random dictionary and latency parameters.

The multi-channel algorithm is executed using all the channels from the input data, while the single-channel algorithm is executed several times, each time using a different channel.

The results of our multi-channel algorithm show:

- A very good fit of the learned dictionary to the generated one.
- A good fit also in the case where the signals were contaminated by noise.

5. Results on real data

The multi-dimensional approach is tested using real MEG and EEG data:

- \( M = 200 \) channels.
- \( M = 63 \) trials.
- \( N = 541 \) time samples.
- Contaminated by ambient noise.

Input parameters:

- \( S = 103 \) contiguous allowed shifts.
- \( K = 3 \) atoms.

6. Conclusions

- The method shows superior performance and less noisy estimated waveforms compared to the original single-channel JADL framework, both on synthetic and real data.
- It is more robust to various levels of noise.
- Using the JADL framework allows one to deal with signal variabilities such as jitters which is difficult to do with standard methods such as PCA or ICA.
- Not having to select a "best" channel (as with the JADL method) is both a user simplification and allows the exploitation of all the available information for M/EEG trial by trial signal decomposition. Thus it provides better estimations of waveforms in the dictionary.

References