Non-Intrusive Load Monitoring of HVAC Components using Signal Unmixing

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NILM is the task of separating aggregate energy signal into the energy signal of the individual components.

- Energy conservation.
- Fault detection.
- Lower costs of sensors and low intrusion installation.
HVAC load monitoring

Heating, Ventilating and Air Conditioning units (HVAC) are a major electrical energy consumer in the buildings.

- Currently account for 57% of the energy used in U.S. commercial and residential buildings.
- HVAC systems commonly operate in a degraded or faulted condition:
  Continous monitoring is therefore crucial to identify the faults at the early stage and making decisions for repair.
Hierarchy disaggregation

- The first step is disaggregation of power signal of the whole building to the power signals of all the circuits and devices existing in the building.
- The second step is decomposition of the obtained HVAC power signal from the last step and estimating the power consumption profile of its components.
Disaggregation using Constrained NMF

\[
\tilde{X} = DA
\]

\[
\hat{A}_{1:k} = \arg\min_{A_{1:k}} \left\| \tilde{X} - [D_1, \ldots, D_k] \begin{bmatrix} A_1 \\ A_2 \\ \vdots \\ A_k \end{bmatrix} \right\|_2^2
\]

(1)

- \( \tilde{X} \in \mathbb{R}^{m \times d} \) is the aggregated signal.
- \( D_i \in \mathbb{R}^{m \times n} \) is the energy consumption of the \( i \)th device.
- Each column of \( D_i \) and \( \tilde{X} \) includes one day of power signal.
- The goal is to build a model which can be used to decompose the aggregated signal to each individual device’s signal.
Signal Estimation:

After calculating the activation coefficient for each device, the estimated signal for the $i$th device would be:

$$\hat{X}_i = D_i \hat{A}_i$$  \hspace{1cm} (2)

$\bar{X} \in R^{m \times d}$, $\hat{X}_i \in R^{m \times d}$, $D_i \in R^{m \times n}$ and $\hat{A}_i \in R^{n \times d}$
**Sum-to-K constraint**

We propose, the sum-to-k constraint for activation coefficients $A$. It means for each $\hat{A}_i \in \mathbb{R}^{n \times d}$ we should have $\sum_{j=1}^{n} A_i(j) = 1$.

$$\hat{A}_{1:k} = \arg\min_{A_{1:k} \geq 0} \left\| \bar{X} - [D_1 \ldots D_k] \begin{bmatrix} A_1 \\ A_2 \\ \vdots \\ A_k \end{bmatrix} \right\|_2^2 + \beta \left\| U - SA \right\|_2^2$$  \hspace{1cm} (3)

- $U \in \mathbb{R}^{k \times d}$ is a matrix with all its entries equal to one.
- $S$ is the matrix including 1 and 0 elements that we would define in some way that it forces the summation of activation coefficients for each device in matrix $A$ to be equal to one ($S$ has $n$ 1’s in each row).
An example:

Assume, we have $k = 4$ devices and $n = 3$ days of training data for each device and $d = 1$ day of testing for aggregated signal. Consequently, the model matrix $D$ would be of size $m \times 12$. By defining $S \in R^{k \times k \times n}$ as the following matrix, we impose sum to $K$ constraint for activation matrix $A$.

$$S = \begin{bmatrix} 111 & 000 & 000 & 000 \\ 000 & 111 & 000 & 000 \\ 000 & 000 & 111 & 000 \\ 000 & 000 & 000 & 111 \end{bmatrix}, \begin{bmatrix} A_1 \\ A_2 \\ A_3 \\ A_4 \end{bmatrix}, A_i \in R^{3 \times 1} \quad (4)$$

This sum-to-$K$ constraint highly increases the accuracy of the disaggregation method.
For solving the optimization problem we use matrix augmentation which leads to solving the following optimization problem:

$$\hat{A} = \arg\min_{A \geq 0} \left\| \begin{bmatrix} \tilde{X} \\ \beta U \end{bmatrix} - \begin{bmatrix} D \\ \beta S \end{bmatrix} A \right\|^2_2$$

(5)

Solving via Fast Non-Negative Least Square (FNNLS)
The data was collected on the Oak Ridge National Lab (ORNL) Flexible Research Platform (FRP1).

There are 16 different devices, circuits and plugs in the building: HVAC unit, 480/208 Transformer, lighting circuits: 1, 3, 5, 7, Plug circuits: 1, 3, 5, 7, cord reel circuit, lighting control box, exhaust fan, piping heat trace, exterior lighting (lighting and emergency) and building control circuit.
Results: Building power decomposition

Table: Disaggregation Error for training and testing stages for building power disaggregation.

<table>
<thead>
<tr>
<th></th>
<th>Training</th>
<th>Testing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GCNMF</td>
<td>DDSC</td>
</tr>
<tr>
<td>DISAG-ERROR</td>
<td>7.5181e − 16</td>
<td>0.091543</td>
</tr>
</tbody>
</table>

Disaggregation Error:

\[ \sum_{i=1}^{k} \frac{1}{2} \left\| X_i - \hat{X}_i \right\|_2^2 \]  

(6)
Results: Building Energy decomposition

Figure: Building power disaggregation. Two top figures: Estimated power consumption profile of the HVAC and lighting control box via GCNMF method during one day. The two bottom figures: Estimated power signals using DDSC method.
Results: HVAC Energy decomposition

Table: RMSE for estimation of power consumption profile of different components of HVAC.

<table>
<thead>
<tr>
<th>HVAC Components</th>
<th>Training-RMSE</th>
<th>Testing-RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1 compressor</td>
<td>7.9729e-19</td>
<td>0.0029</td>
</tr>
<tr>
<td>C1 condenser fan</td>
<td>0</td>
<td>0.00017</td>
</tr>
<tr>
<td>C2 compressor</td>
<td>0</td>
<td>0.00049</td>
</tr>
<tr>
<td>C2 condenser fan</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Indoor blower</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Results: HVAC decomposition: ORNL dataset

Figure: Estimated power consumption profile of compressor (left) and condenser fan (right) of HVAC unit for one day using GCNMF.
Summary:

- Proposed method based on constrained NMF outperforms the state of the art load disaggregation methods.
- Also:
  - Works with low sampling rate data (1 sample per Min).
  - Does not need big training data.
  - Uses real aggregated signal instead of summation of the devices signals.

Future work:
- Online and unsupervised load disaggregation
- Fault detection using NILM
Thanks for your attention!

Questions/Comments?