
Prediction of Epileptic Seizures using Machine Learning and Deep Learning models

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I certify that except where due acknowledgement has been given, the work presented in this thesis is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; and the content of the thesis is the result of work which has been carried out since the official commencement date of the approved research program.

Alessia Ruggeri
Lugano, 5th September 2019

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Acronyms

Adam	adaptive moment estimation
AI	artificial intelligence
AUC	area under the curve
CNN	convolutional neural network
DRE	drug-resistant epilepsy
ECC	edge-conditioned convolution
EEG	electroencephalogram
FCNN	fully-connected neural network
GCN	graph convolutional network
GNN	graph neural network
iEEG	intracranial electroencephalogram
LSTM	Long short-term memory
ML	machine learning
MRI	magnetic resonance imaging
MSE	mean squared error
NN	neural network
μV	nanovolts
RBF	radial basis function

ReLU rectified linear unit

RNN recurrent neural network

ROC receiver operating characteristic

SVM Support Vector Machine

Tanh hyperbolic tangent

Chapter 1

Implementation

In this chapter we present the tools that have been used for the implementation of the project, some details about the data, the data preprocessing procedure, a description of the models' configurations and experiments conducted and the produced results.

1.1 Tools

All the computation for this project has been conducted on a university server equipped with Ubuntu SMP version 16.04.1 and a NVIDIA TITAN Xp graphics card for the deep learning training processes. A brief description of the software tools used for the project will follow.

Python [1] The programming language used for this project is Python v3.6. Python is a general purpose language, known for its ease of use and understanding; however, thanks to the addition of dedicated libraries for data analysis and predictive modeling, in the last few years it has become the reference and most-used language for data science.

Numpy [2] Numpy is an extremely popular and useful library for scientific computing with Python. It allows to easily handle multidimensional data through matrix representation and to perform operation between them thanks to its broadcasting functions. Numpy has been used in all the project implementation's steps to handle and manipulate the data.

Pandas [3] Pandas is an open source library which provides efficient, flexible and easy-to-use data structures and data analysis tools for Python. Pandas is built on top of Numpy library and it is suited to handle almost any kind of data, representing them in a handy tabular form. We mainly used Pandas in order to store the results from the experiments.

matplotlib [4] Matplotlib is a 2D plotting library and it represents one of the most common visualization tools for Python. Its `pyplot` module provides a MATLAB-like functional interface and a wide degree of customization of the generated figures. All the plots in this thesis has been generated using matplotlib library.

scikit-learn [5] Scikit-learn is a well-known, simple and efficient library for data analysis and machine learning in Python. It is open-source and is built on NumPy, SciPy, and matplotlib libraries. It provides several useful tools for data preprocessing, model selection, classification, regression, clustering and dimensionality reduction. In this project, it has been heavily used for the data preprocessing and to implement the classic machine learning models.

XGBoost [6] XGBoost is an optimized library for distributed gradient boosting, designed to be highly efficient, flexible and portable. It implements a tree-based gradient boosting model which has been used for the gradient boosting experiments.

Tensorflow & Keras [7] [8] The framework we used in order to build deep learning models is Tensorflow v2.0. Tensorflow is one of the most popular frameworks for machine learning and deep learning; it is open-source and it provides a flexible ecosystem of tools, libraries and community resources to easily build machine learning models. On top of Tensorflow, we used Keras high-level neural networks API. Keras was originally a library separated from Tensorflow, providing ready-to-use tools for fast experimentation and developing of neural networks models by running on top of TensorFlow, CNTK, or Theano. With the update to version 2.0 of Tensorflow, Keras has officially become part of Tensorflow API. We mainly used Keras library on top of Tensorflow for the implementation of deep learning models in order to generate high-level and easy-to-understand code. This choice was reasoned by the fact that this thesis project is also related to the medical field, so we tried to make the code readable also by people which are not specialized in the data scientist field.

Spektral [9] Spektral is a Python library for graph deep learning, based on the Keras API. It provides a simple but flexible framework for creating graph neural networks (GNNs) by making available several ready-to-use, but still highly customizable, graph-based deep learning layers. It also implements functions for the creation of the functional connectivity network from a data stream. In this project, Spektral library was used for the generation of functional connectivity graphs and for the implementation of graph-based deep learning models.

1.2 Data analysis

For this project, we were provided with 24 hours of iEEG data generated from real measurements on a patient suffering form epilepsy. The data contains three seizures, all happening during the first three hours of recording; therefore just the data regarding the first three hours have been used in the project. The brain activity has been measured using 90 electrodes and a sampling frequency of 500 Hz, so each hour contains 1 800 000 time steps of measurements.

First thing, we identified the position of the seizures in the data and their length. As already mentioned, the data contains three seizures in total, each one having a duration between 13 000 and 15 000 time steps, for a total of 42 000 time steps of seizure. This corresponds to 26 to 30 seconds of duration for each seizure and 84 seconds of seizure in total. Since the most important data for this project were the seizure time steps and we didn't need a huge amount of non-seizure time steps, during all the project we considered only a portion of data around each one of the three seizures, obtaining 450 000 time steps (15 minutes) to work with between seizure and non-seizure data in total. This should give an idea of how much limited the amount of useful data was for this project.

Some basic statistical measurements have been applied to the iEEG data in order to familiarize with its features. The measured voltage in the iEEG vary between about -9500 and $9800 \mu\text{V}$ (microvolts), covering a range of about $19300 \mu\text{V}$. Each electrode's signal oscillate through time with a standard deviation of around $82 \mu\text{V}$ and the various electrodes signals cover different areas of the iEEG voltage range based on their placement on the brain surface. In Figure 1.1 the plots of the iEEG around the three seizures is shown. The start and end times of the seizures in each plot are indicated by red vertical lines.

Change following
3 iEEGs to high-
quality correspond-
ing images

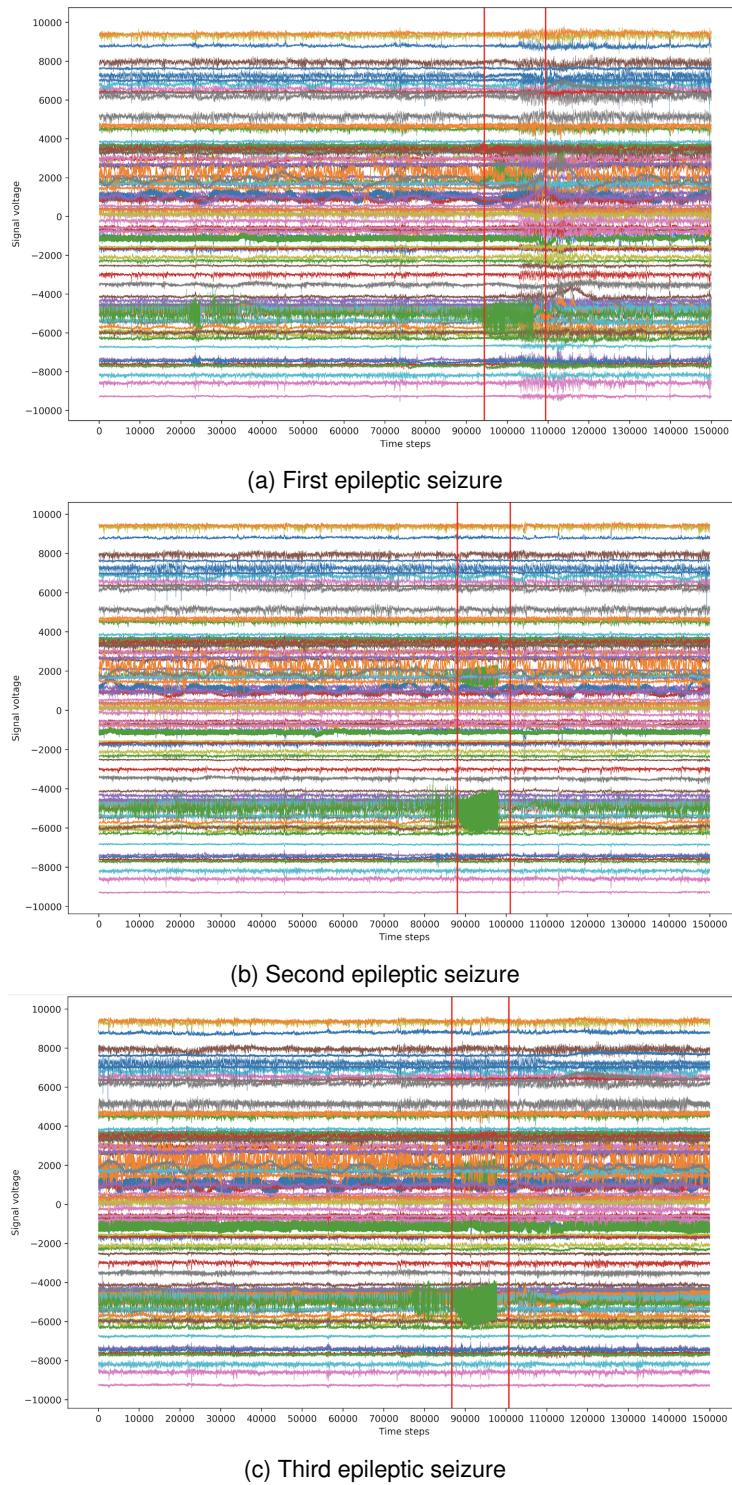


Figure 1.1. Plots of the iEEG around the three epileptic seizures (we suggest to zoom-in the figures in the pdf file)

Looking at Figure 1.1, it seems like the iEEGs is not able to explicitly show the presence of a seizure, since the dynamic of the electrodes signals doesn't seem to undergo a big change in correspondence of the beginning of a seizure. This behaviour suggests that the seizure could not be directly represented by the dynamic of the signals, but it could be represented by the non-linear relations between the electrodes signal's dynamic through time.

The amount of positive time steps, that are the ones inside the seizure portions, corresponds only to the 9.3% of the data, with the remaining 90.7% of data being negative time steps; therefore we are dealing with very unbalanced data (see Figure 1.2). The extreme unbalance of the data, together with the severe restriction in the amount of data, make this dataset very difficult to work with, but at the same time very similar to a real-world scenario.

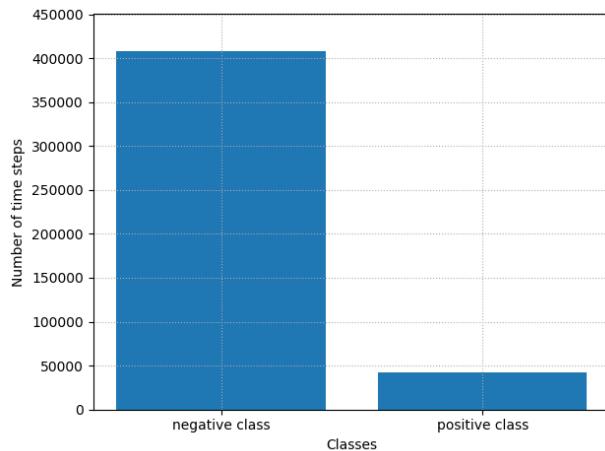
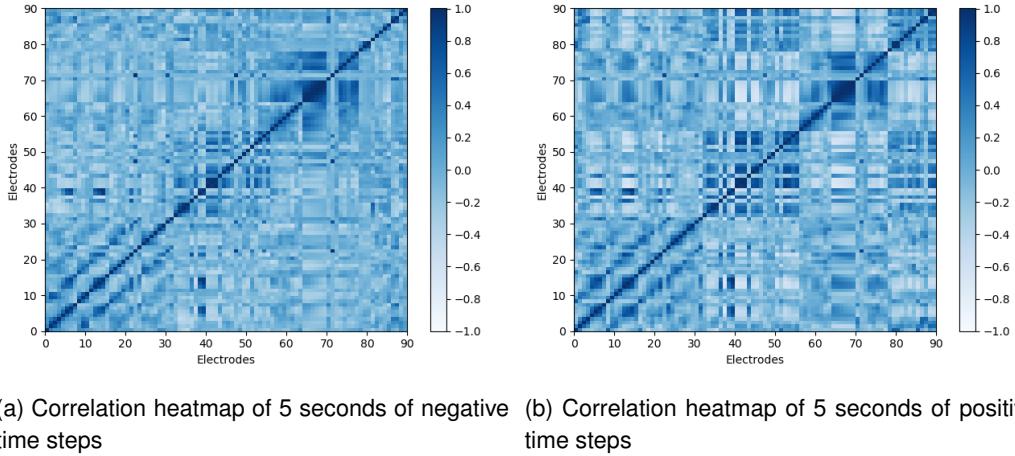


Figure 1.2. Histogram of the number of time step for each class

In order to have an idea of the linear relation between electrodes values, we computed the Pearson correlation coefficient on two sequences of 5 seconds each, one of negative time steps and the other of positive time steps. In Figure 1.3 we show the related correlation heatmaps. As you can see from the figures, the correlation heatmap related to the positive time steps reveals a higher linear relation between electrodes values if compared to the correlation heatmap related to the negative time steps. The correlation heatmaps, however, present only the linear relations between data, while we believe that there are hidden non-linear relation between electrodes signal through time which could be crucial for the identification of epileptic seizures.

To have another confirmation of the presence of some linear relation between electrodes signals, we computed the standard deviation of the oscillation of each electrode,



(a) Correlation heatmap of 5 seconds of negative time steps (b) Correlation heatmap of 5 seconds of positive time steps

Figure 1.3. Comparison of correlation heatmaps related to negative and positive time steps

but this time we computed the mean of the standard deviation both over the negative time steps and over the positive ones. The average standard deviation of the oscillation of each electrode over the negative time steps was around $80 \mu\text{V}$, while the one over the positive time steps was around $93 \mu\text{V}$. This shows that, during an epileptic seizure, electrodes signals tends to have wider fluctuation margins, but the difference from the standard fluctuation margins doesn't seem to be enough to identify a seizure.

1.3 Data preprocessing

Once we familiarized with the dataset, we preprocessed it in order to shape it to the right form to be the input of machine learning and deep learning models for the different prediction tasks. As already mentioned in Section ??, we divided the data in a training set and a test set, using two seizures' data in the training set and the remaining seizure's data in the test set. We sacrificed the validation set for lack of data. Then the data was prepared to be used by different models for the three prediction tasks described in Section ?? . Depending on the model and on the task at hand, a sample could represent a time step, a sequence of samples or a sequence of graphs.

- 1.3.1 Time steps as samples
- 1.3.2 Sequences of time steps as samples
- 1.3.3 Sequences of graphs as samples
- 1.3.4 Cross-validation

1.4 Experiments

- 1.4.1 Support Vector Machine experiments
- 1.4.2 Random forest experiments
- 1.4.3 Gradient boosting experiments
- 1.4.4 Dense neural network experiments
- 1.4.5 Convolutional neural network experiments
- 1.4.6 LSTM neural network experiments
- 1.4.7 Graph-based LSTM neural network experiments
- 1.4.8 Graph-based convolutional neural network experiments

1.5 Results

- 1.5.1 Experiments results

Notes

Topics

- Intro (big summary of the thesis)
 - Problem statement
 - What (GNN, LSTM, etc.)
- Background (theoretical explanation of models used and SOTA)
 - Machine learning methods
 - Neural Networks
 - Dense
 - LSTM
 - Conv
 - GNN
 - Seizure prediction
 - EEG
 - Functional connectivity network
 - State of the art
- Methods (description of all the work done and motivations, but no numbers)
 - Baseline
 - Graph / contribution
- Experiments/Implementation (technical description of all the work done with parameters and numbers)
 - Environment (software, server, framework)
 - Data + preprocessing

Architectures (params)

Results

- Conclusions

Comments

Future work

Project steps

- Baseline

Detection

— Random Forest

— Gradient Boosting

— SVM

— Dense

— LSTM

— Convolution

Prediction

— LSTM

— Convolution

— Stride > 1 and bigger look_back

— Parameters search

- Graph Neural Networks

GNN + LSTM

GNN + Conv1D

TODO Pooling

— **TODO** Hierarchical (Rex Ying)

— **TODO** Decimation (Bianchi)

- Baseline

TODO Cross Validation on 3 seizures

TODO Bayesian optimization

TODO Different functional connectivity nets

TODO Big data

TODO Structural connectivity (KNN)

Missing experiments: Detection with graph-based models, cross-validation on detection tasks

1.6 General considerations

1.6.1 IEEG plots

The ieeg plots give an overall idea of the type of data to deal with and of the shape of the patient's seizures. On 24 hours of recording, there are three seizures in the first 3 hours. The data is divided in clips of 1 hour each, containing 1800000 timestamps each (the signal is sampled at 500Hz). The three seizures found have a duration between 13000 and 15000 timestamps each (between 26 and 30 seconds).

The ieeg doesn't explicitly show the presence of a seizure; indeed the dynamic of the electrodes signals doesn't change in correspondence of the beginning of a seizure. For example, in the first seizure the signals dynamic remains pretty stable during the first half of the seizure and suddenly changes at the beginning of the second half of the seizure. This behaviour suggests that the seizure is not directly represented by the dynamic of the signals, but it is represented by the non-linear relations between the electrodes behaviours.

The ieeg plots show an interesting thing: in all the three seizures, there are two electrodes that are more dynamic exactly during the seizure. In the plots they are always represented with green colour.

- classic plot (with y values): electrodes signals positioned at -5000 and 2500.
- norm plot (y normalised): electrodes signals positioned at 8th position from the top and 33th position from the bottom.

1.7 Machine learning classic models

1.7.1 Experiments with classic methods

The three machine learning classic methods used to perform experiments are random forest, gradient boosting and support vector machine. All the three methods have been

implemented using scikit learns modules; for gradient boosting also xgboost library has been used. For all the experiment just portions containing seizures of the entire dataset have been used to train and to test data in order to speed up the process and to reduce the huge difference of availability of data between the two classes.

Classic methods have been used only for the detection task, since they are not powerful enough in order to deal with the prediction task, at least with this kind of data.

Parameters:

- random forest:

number of estimators: 100

maximum depth: 10

both balanced and non-balanced class weight

- gradient boosting:

number of estimators: 100

maximum depth: 10

- svm:

gamma: scale

both weighted and non-weighted classes

In all the experiments, seizure 2 and 3 have been used as training set, while seizure 1 has been used as test set.

Maybe try to cross-validate by exchanging datasets for training and testing.

Results: All the experiments had almost the same results:

- Loss: around 0.15
- Accuracy: around 0.85
- Roc auc: around 0.65

Only the unbalanced random forest was able to get almost decent results:

- Loss: 0.11
- Accuracy: 0.85

- Roc auc: 0.73

The results are very bad and show that the classic methods are too weak to be able to solve this problem having to deal with such a complex and unbalanced dataset. Indeed, the area under the Roc curve is around 0.65 for the majority of the models, which means that the predictions are made almost in a random way.

Maybe try using some different metric (ex. F1)

The predictions have also been plotted in order to have a better idea of what was predicted wrong and where and also the plots show a non-logical distribution, even if in some cases (for example in the non-balanced experiment with the random forest) the predictions in the seizure area seem to match with the targets. Also in the gradient boosting experiment, the model seems to start predicting 1 (there is a seizure) in the same timestamps in which the signals in the ieg start to be more dynamic (almost in the middle of the seizure 1).

1.8 Deep learning classic models

1.8.1 Dense neural network

A dense neural network have been built in order to deal with the seizure detection task. After some hyperparameters tuning, the final structure of the network was the following:

Parameters: These are the parameters used in the network's layers.

- activation: tanh
- kernel regularisation: L2(5e-4)
- class weight: {0: len(y_train) / n_negative, len(y_train) / n_positive}

Structure: These are the layers used to build the network.

```

1 Dense(units: 512)
2 Dropout(0.5)
3 Dense(units: 512)
4 Dropout(0.5)
5 Dense(units: 256)
6 Dropout(0.5)
7 Dense(units: 1, activation: 'sigmoid')
```

In order to compile the model, binary cross-entropy has been used as loss and Adam as optimiser.

Initially the structure was composed by less layers and each one with less units (ex. 128, 156), but the model wasn't powerful enough so both the number of layers and units have been increased. The kernel regularisation and the dropout layers have been added in order to avoid overfitting on training data. For the activation of the dense layers, both tanh and ReLu have been tried, but for some reason tanh works way better. Since the two classes of the problem, that are "seizure" (1) and "not-seizure" (0), are very unbalanced due to the small presence of seizure timestamps with respect to the number of non-seizure timestamps, class weight has been used to train the network. The weight assigned to each class is inversely proportional to the number of timestamps of that class with respect to the total number of timestamps.

Initially, in order to preprocess the data, the MinMaxScaler from scikit-learn library was used, but then it was substituted by the StandardScaler because this one led to better performances. The data are also shuffled in order to help the network to generalise.

Initially, as for the machine learning classic methods, just portions containing seizures of the entire dataset have been used to train and to test data. In order to do some test, a modification of the initial dataset has been tried: the dataset has been modified so that each clip is trimmed ending with the end of the seizure and starting 100,000 timestamps before the end of the seizure. The intention of this test was to eliminate the useless bias generated by the timestamps after the seizure. However, after testing it, for some reason the results got a lot worse, so the old portions of the dataset have been used for the next experiments.

Results After all the tuning described above, the best results that the dense network got on the detection task were the following:

- Loss: 0.87
- Accuracy: 0.79
- Roc auc: 0.74

These results are not extremely good but they are ok considering the complexity of the problem. The dense network behaved in a similar way to the unbalanced random forest, looking at the results. Looking at the plots of the predictions, they don't seem to be very promising, but in order to better understand the behaviour of the prediction, also the running mean have been plotted and it explicitly shows that the network is able to understand where is the seizure.

A strange thing happens in the predictions: in the test prediction plot, there is a sort of a "hole" of zero predictions right after the end of the seizure.

1.8.2 LSTM neural network

I built an LSTM network in order to deal both with the detection and the prediction tasks.

For this network, I introduced subsampling to the data preprocessing. The subsampling function take as input the subsampling factor, which represent how many negative examples we want to keep with respect to the positive ones. In this way, we can consistently reduce the disparity in the amount of positive and negative examples, preserving all the positive ones. The subsampling was performed both for the detection and the prediction task. The subsampling factor was set to 2, so that for each positive samples there are two negative ones. The stride in the subsampling was set to 1 in order to keep all the (positive) samples.

Another function was used in order to generate the sequences of data and labels to give as input to the network. It takes the parameters "look_back", which is the length of the input sequence (how many samples do I look behind), and "target_steps_ahead", which represents how many steps ahead to predict (how many samples there are between the end of the input sequence and the future sample I want to predict). Given this two parameters, it creates the pairs input_sequence - target accordingly.

For the detection task, the parameter "target_steps_ahead" was set to 0, that is the target corresponding to the last sample of the input sequence. For the prediction task, obviously the parameter was set to some values higher than 0, as we want to predict the target of a sample in the future, that wasn't inside the input sequence.

Detection task For the detection task, after some hyperparameter search and tuning, the best result was given by these parameters (experiment 147):

```

1 epochs:      10
2 batch_size:   64
3 depth_lstm:   1
4 depth_dense:  2
5 units_lstm:  256
6 reg:          l2(5e-1)
7 activation:   relu
8 batch_norm:   True
9 dropout:      0.4

```

```

10 class_weight: {0: 0.4682, 1: 3.0}
11 look_back: 100
12 stride: 1
13 predicted_timestamps: 1
14 target_steps_ahead: 0
15 subsampling_factor: 2

```

The network was build in this way:

```

1 LSTM(units: 256)
2 BatchNormalization()
3 Dropout(0.4)
4 Dense(units: 256)
5 BatchNormalization()
6 Dropout(0.4)
7 Dense(units: 1, activation: 'sigmoid')

```

The results on an input sequence of length 100 were:

- Loss: 0.2632
- Accuracy: 0.9059
- Roc auc: 0.9263

Prediction task For the prediction task, after some hyperparameter search and tuning, the best result was given by these parameters (experiment 20):

```

1 epochs: 10
2 batch_size: 64
3 depth_lstm: 1
4 depth_dense: 2
5 units_lstm: 256
6 reg: l2(5e-1)
7 activation: relu
8 batch_norm: True
9 dropout: 0.4
10 class_weight: {0: 1.1561, 1: 7.4074}
11 look_back: 200
12 stride: 1
13 predicted_timestamps: 1
14 target_steps_ahead: 2000
15 subsampling_factor: 2

```

The network was build in this way:

```

1 LSTM(units: 256)
2 BatchNormalization()
3 Dropout(0.4)
4 Dense(units: 256)
5 BatchNormalization()
6 Dropout(0.4)
7 Dense(units: 1, activation: 'sigmoid')
```

The results on an input sequence of length 100 and a target steps ahead of 2000 were:

- Loss: 0.3098
- Accuracy: 0.9454
- Roc auc: 0.9337

The network that performed better was the same for both the detection and prediction tasks, even with the same regularisation parameters. What changed was, of course, the distance of the sample predicted and the length of the input sequence. The LSTM, in both the situation, wasn't able to deal with more than 200 samples in the input sequence (the results were way worse with a higher value). For the prediction task, the network was able to successfully predict until 2000 steps ahead, which correspond to 4 seconds. Higher than that, the prediction became almost random.

1.8.3 Convolutional neural network

I built a CNN in order to deal both with the detection and the prediction tasks.

For this network, as for the LSTM, I introduced subsampling to the data preprocessing (see LSTM). The subsampling was performed both for the detection and the prediction task. The subsampling factor was set to 2, so that for each positive samples there are two negative ones. Another function was used in order to generate the sequences of data and labels to give as input to the network (see LSTM).

Detection task For the detection task, we used the same parameter we found for the LSTM, except for the look_back, that in the case of the convolutional can be much higher. The best result was given by these parameters (experiment 2):

```
1 epochs:      10
2 batch_size:   64
3 depth_conv:   5
4 depth_dense:  2
5 filters:      512
6 kernel_size:  5
7 reg:          l2(5e-1)
8 activation:   relu
9 batch_norm:   True
10 dropout:     0.4
11 class_weight: {0: 1.1561, 1: 7.4074}
12 look_back:    1000
13 stride:      1
14 predicted_timestamps: 1
15 target_steps_ahead:    0
16 subsampling_factor:    2
```

Run again experiments for detection with CNN using less filters and smaller kernel size

The network was build in this way:

```
1 Conv1D(filters: 512)
2 MaxPooling1D()
3 Conv1D(filters: 512)
4 MaxPooling1D()
5 Conv1D(filters: 512)
6 MaxPooling1D()
7 Conv1D(filters: 512)
8 MaxPooling1D()
9 Conv1D(filters: 512)
10 MaxPooling1D()
11 Flatten()
12 Dense(units: 256)
13 BatchNormalization()
14 Dropout(0.4)
15 Dense(units: 1, activation: 'sigmoid')
```

The results on an input sequence of length 1000 were:

- Loss: 0.1550
- Accuracy: 0.9374

- Roc auc: 0.9870

Prediction task For the prediction task, I began with some hyperparameter search and tuning using the same parameters used for the LSTM as initial model. The best result was given by these parameters (experiment 29):

```

1 epochs:      10
2 batch_size:   64
3 depth_conv:   5
4 depth_dense:  2
5 filters:     256
6 kernel_size: 5
7 reg:          l2(5e-1)
8 activation:   relu
9 batch_norm:   True
10 dropout:    0.4
11 class_weight: {0: 1.1560, 1: 7.4074}
12 look_back:   1000
13 stride:     1
14 predicted_timestamps: 1
15 target_steps_ahead:    2000
16 subsampling_factor:   2

```

The network was build in this way:

```

1 Conv1D(filters: 256)
2 MaxPooling1D()
3 Conv1D(filters: 256)
4 MaxPooling1D()
5 Conv1D(filters: 256)
6 MaxPooling1D()
7 Conv1D(filters: 256)
8 MaxPooling1D()
9 Conv1D(filters: 128)
10 MaxPooling1D()
11 Flatten()
12 Dense(units: 256)
13 BatchNormalization()
14 Dropout(0.4)
15 Dense(units: 1, activation: 'sigmoid')

```

The results on an input sequence of length 100 and a target steps ahead of 2000 were:

- Loss: 0.2598
- Accuracy: 0.9314
- Roc auc: 0.9274

For the prediction task, the network was able to successfully predict until 2000 steps ahead, which correspond to 4 seconds. Higher than that, the prediction became almost random.

CNN notes

Bibliography

- [1] Python. URL <https://www.python.org/>. [Online; accessed 16-August-2019].
- [2] Numpy. URL <https://www.numpy.org/>. [Online; accessed 16-August-2019].
- [3] Pandas. URL <https://pandas.pydata.org/>. [Online; accessed 16-August-2019].
- [4] matplotlib. URL <https://matplotlib.org/>. [Online; accessed 16-August-2019].
- [5] scikit-learn. URL <https://scikit-learn.org/>. [Online; accessed 16-August-2019].
- [6] Xgboost. URL <https://xgboost.readthedocs.io/en/latest/>. [Online; accessed 16-August-2019].
- [7] Tensorflow. URL <https://www.tensorflow.org/>. [Online; accessed 16-August-2019].
- [8] Keras. URL <https://keras.io/>. [Online; accessed 16-August-2019].
- [9] Grattarola Daniele. Spektral. URL <https://github.com/danielegrattarola/spektral>. [Online; accessed 16-August-2019].