

Assignment 4

Modulation Classification

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1 Data Set

The data set is DeepSig Dataset: RadioML 2016.10b, A synthetic dataset, generated with GNU Radio, consisting of 10 modulations. This is a variable-SNR dataset with moderate LO drift, light fading, and numerous different labeled SNR increments for use in measuring performance across different signal and noise power scenarios. The data set consists of 1,200,000 sample signals. Each sample has 2 feature vectors (channels) consisting of 128 element. A sample is labeled with a modulation type and an SNR value. Data set is split into 70% for training and validation and 30% for testing, 5% of the training set is used for validation.

2 Feature spaces

In addition to the raw time series features (2 channels), there are 2 more generated features spaces, first derivative in time (two channels) and integral in time (two channels). Due to memory constraints, only one additional feature space is used with the original raw features.

2.1 first derivative in time

For this feature, the function 'numpy.gradient' is used to find the gradient at each point in the time series. It extracts 2 more 128-long feature vectors.

2.2 integral in time

For this feature, the function 'scipy.integrate.cumtrapz' is used to find the cumulative integration at each point in the time series using the trapizoidal rule. It extracts 2 more 128-long feature vectors.

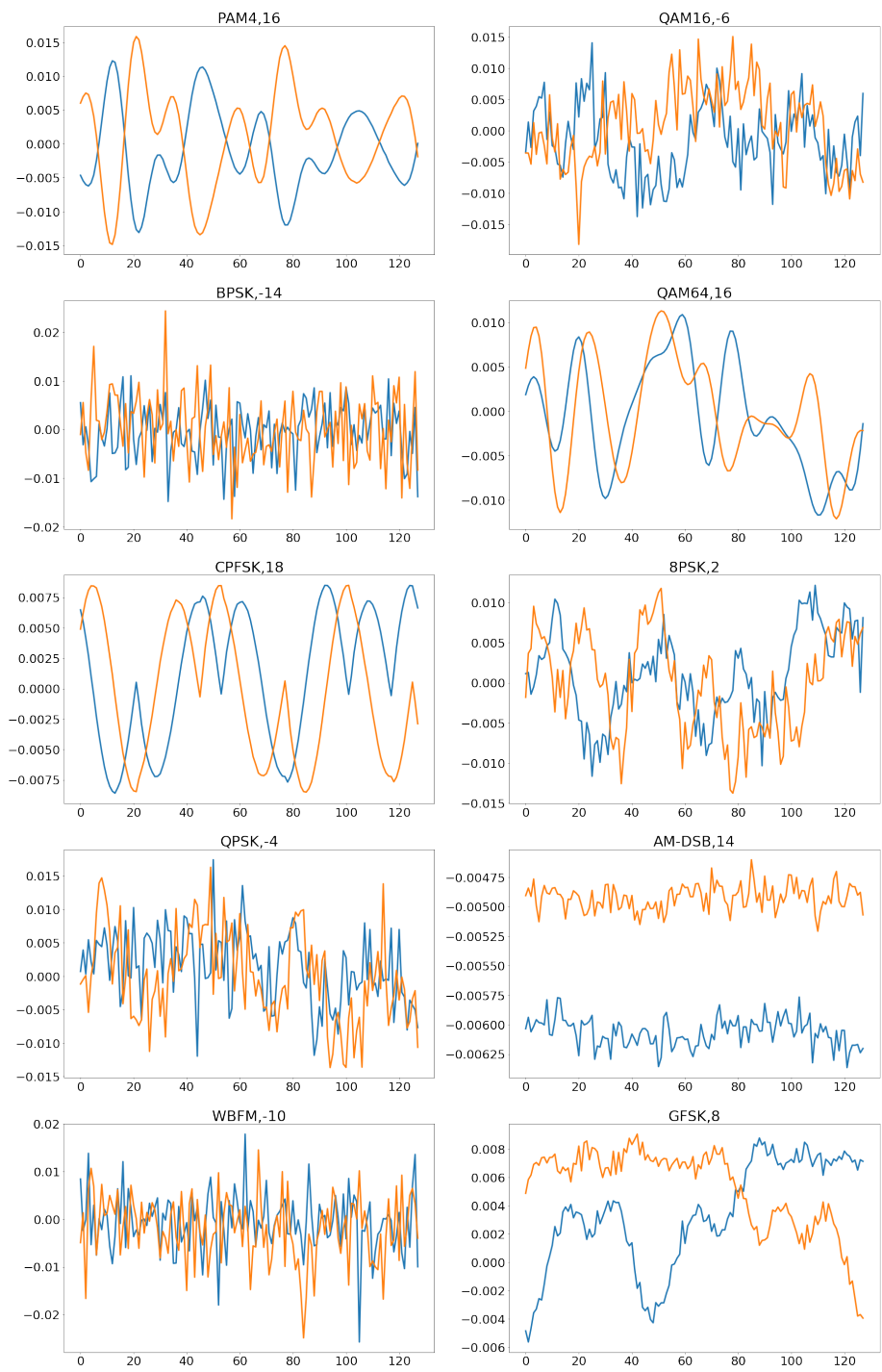


Figure 1: Modulations

3 Data processing

The data set file 'RML2016.10b.dat' is loaded into a Pandas DataFrame in a key-value format using 'pd.read_pickle'. keys are tuples of the modulation class and the SNR value. Value is a list of samples with 2 feature vectors. The DataFrame is reformatted later into a 3D Numpy array with dimensions 1,200,000 x 128 x 2. One of the new features are added later to the raw data, forming a 1,200,000 x 128 x 4 Numpy array.

3.1 Normalization

Min-Max normalization is performed to make sure all elements lie within the range $[-1, 1]$. When a model is fit on unscaled data that has a range of values, it is possible for large inputs to slow down the learning and convergence of the models.

4 Models

4.1 CNN Model

4.1.1 Feature Space

Table 1 shows the training and validation accuracy after 20 epochs, for 3 different combinations of features with Adam optimizer with learning rate of 0.0005. The raw time series features has the best results.

features combination	training accuracy	validation accuracy
raw time series	0.5520	0.5416
raw time series integral in time	0.5446	0.5377
raw time series First derivative in time	0.5175	0.4979

Table 1: Comparing different features combinations in CNN.

4.1.2 Model Structure

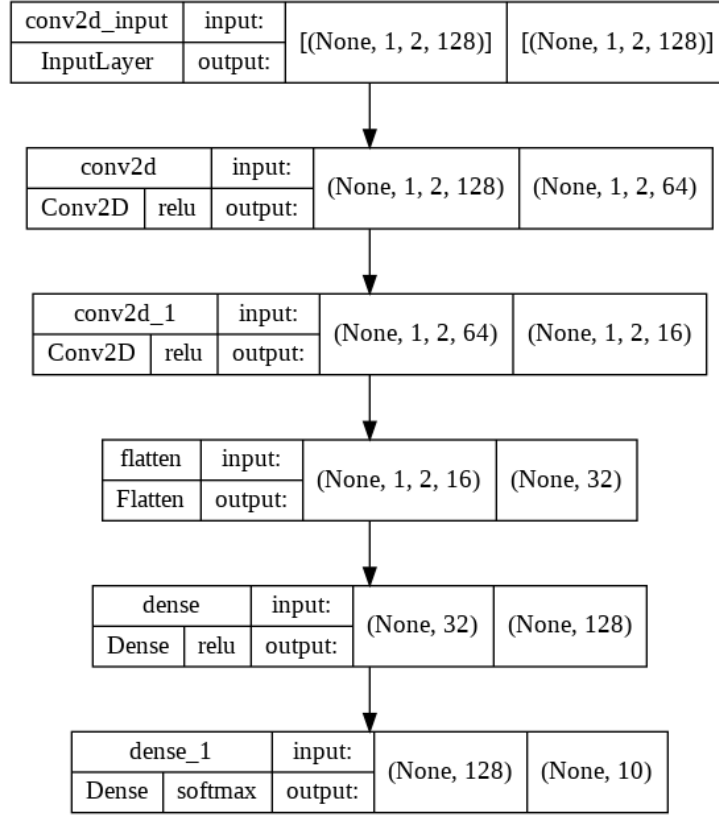


Figure 2: CNN Model

4.1.3 Learning Rate Tuning

Table 2 shows validation accuracy of different learning rates for Adam optimizer. The raw time series feature (2 channels) is used.

lr = 0.001	lr = 0.0005	lr = 0.0001
0.5142	0.5480	0.5015

Table 2: Tuning results of CNN model after 14 epoch

4.1.4 Training

The final model has the following characteristics:

- Adam optimizer with learning rate = 0.0005

- Training accuracy = **55.20%** after **26** epochs
- Validation accuracy = **54.16%**
- Trained with raw time series features only

4.1.5 Big Picture

- The model has an overall accuracy : **53.49%**
- overall confusion matrix:

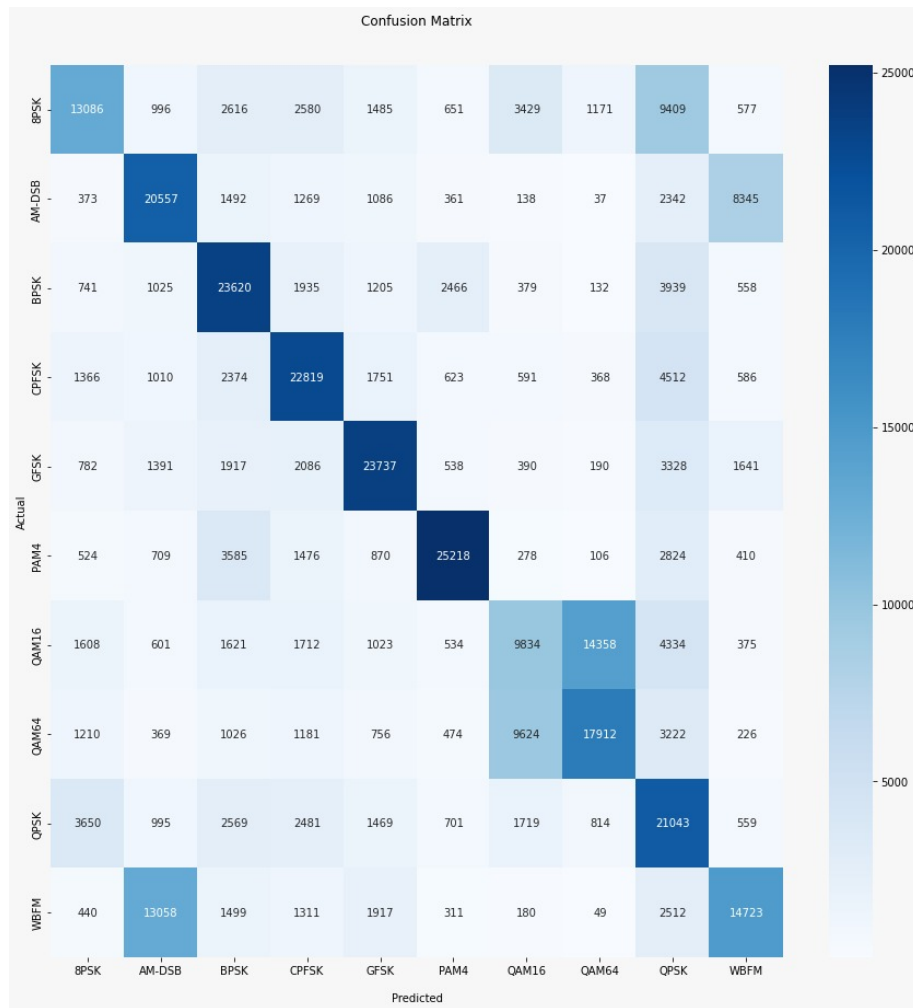


Figure 3: Confusion matrix of the CNN model

- The most confusing class is QPSK, AM-DSB and WBFM are usually confused together.

- accuracy against the SNR :

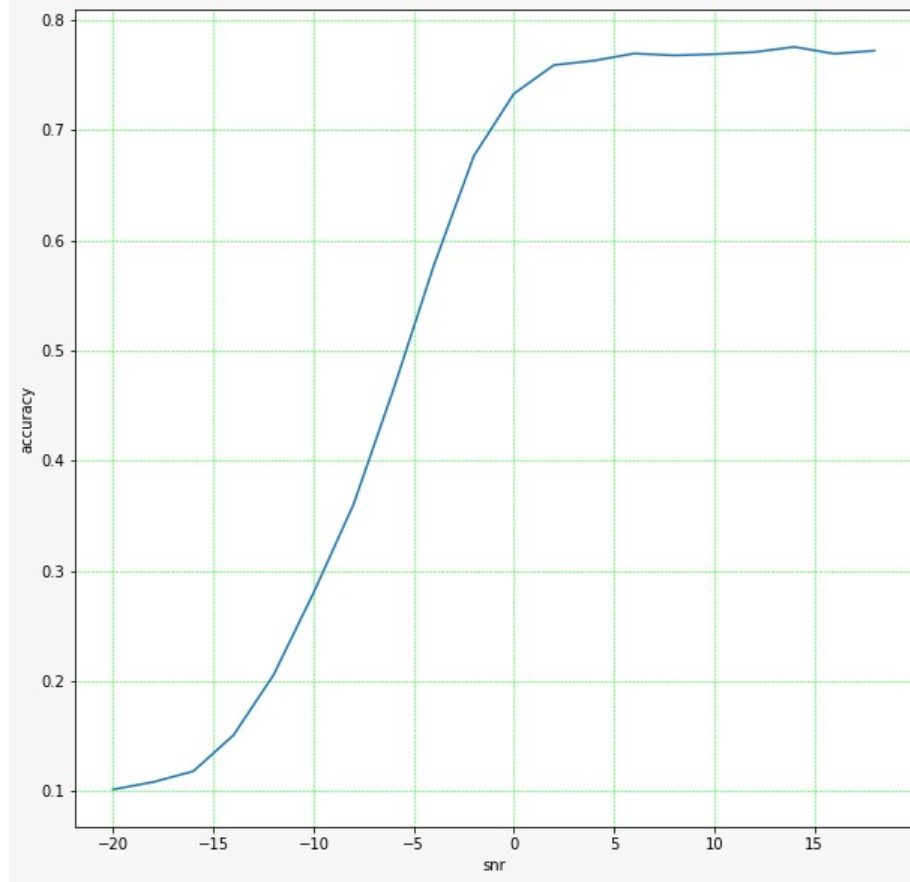


Figure 4: Accuracy vs SNR plot for the CNN model

- the results at SNR=0dB : **73.34%**

4.2 Vanilla RNN Model

4.2.1 Feature Space

Table 3 shows the training and validation accuracy after 10 epochs, for 3 different combinations of features with Adam optimizer with learning rate of 0.0001. The raw and integral in time features combination has the best results

features combination	training accuracy	validation accuracy
raw time series	0.3938	0.3969
raw time series integral in time	0.4896	0.4958
raw time series First derivative in time	0.4286	0.4354

Table 3: Comparing different features combinations for the RNN model.

4.2.2 Model Structure

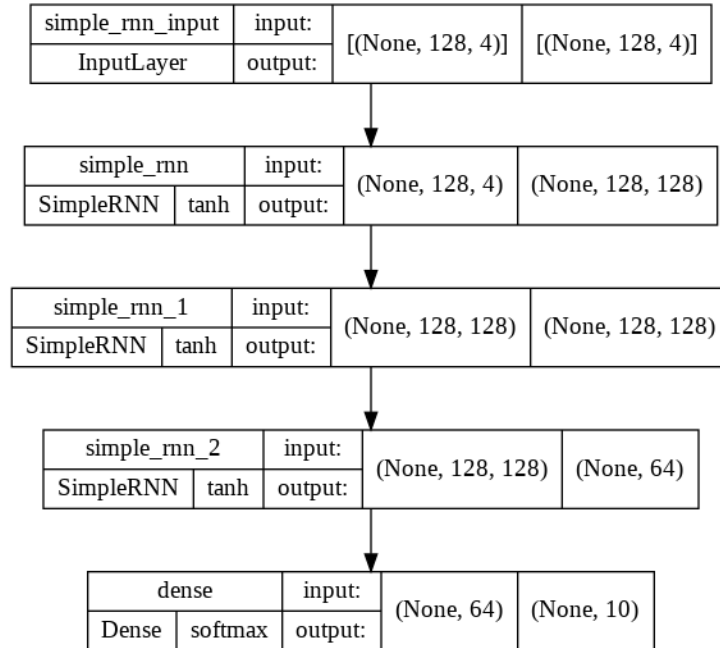


Figure 5: Vanilla RNN Model

4.2.3 Learning Rate Tuning

Table 4 shows validation accuracy of different learning rates for Adam optimizer. The raw time series and integral in time features (4 channels) are used. After 30 epochs with learning rate = 0.0001, Validation accuracy reaches 0.5315.

epoch	lr = 0.001	lr = 0.005	lr = 0.0001	lr = 0.0003
1	0.1866	0.1255	0.3217	0.3830
2	0.1915	0.1265	0.3687	0.3872
3	0.2032	0.1265	0.3913	0.4373
4	0.2030	0.1234	0.3804	0.3902
5	0.2103	0.1243	0.4266	0.4519
6	0.2252	0.1262	0.4785	0.4662
7	0.2271	0.1254	0.4845	0.2688
8	0.2355	0.1236	0.4922	0.3838
9	0.2376	0.1271	0.4901	0.3284
10	0.2368	0.1262	0.4958	0.2627

Table 4: Tuning results on Vanilla RNN model with raw data with integral in time features.

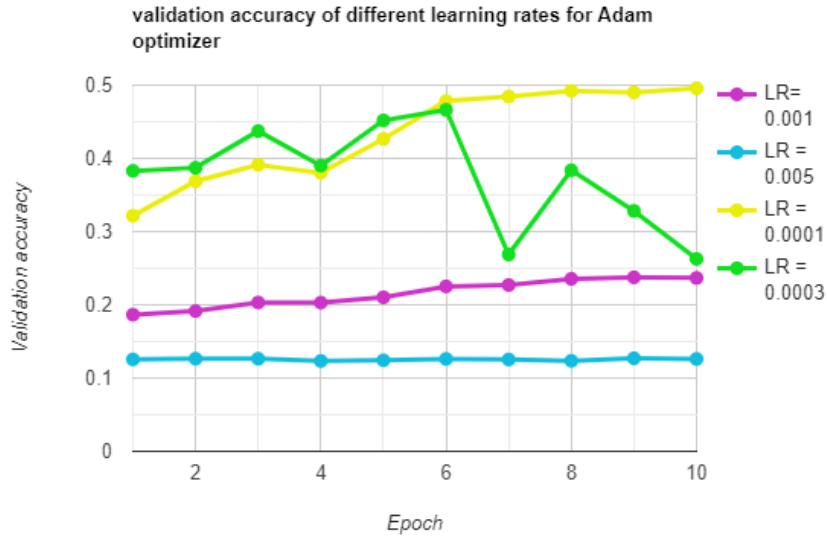


Figure 6: Learning rate plot of Vanilla RNN model with raw data with integral in time features.

4.2.4 Training

The final model has the following characteristics:

- Adam optimizer with learning rate = 0.0001
- Training accuracy = **52.92%** after 30 epochs
- Trained with raw time series + integral in time features

- Validation accuracy = **53.15%**

4.2.5 Big Picture

- The model has an overall accuracy : **52.52%**
- Overall confusion matrix:



Figure 7: Confusion matrix of the Vanilla RNN Model.

- The most confusing classes are (AM-DSB with WBFM), (8PSK with QPSK). QAM16 and QAM64 are usually predicted as QAM64.

- Accuracy against the SNR :

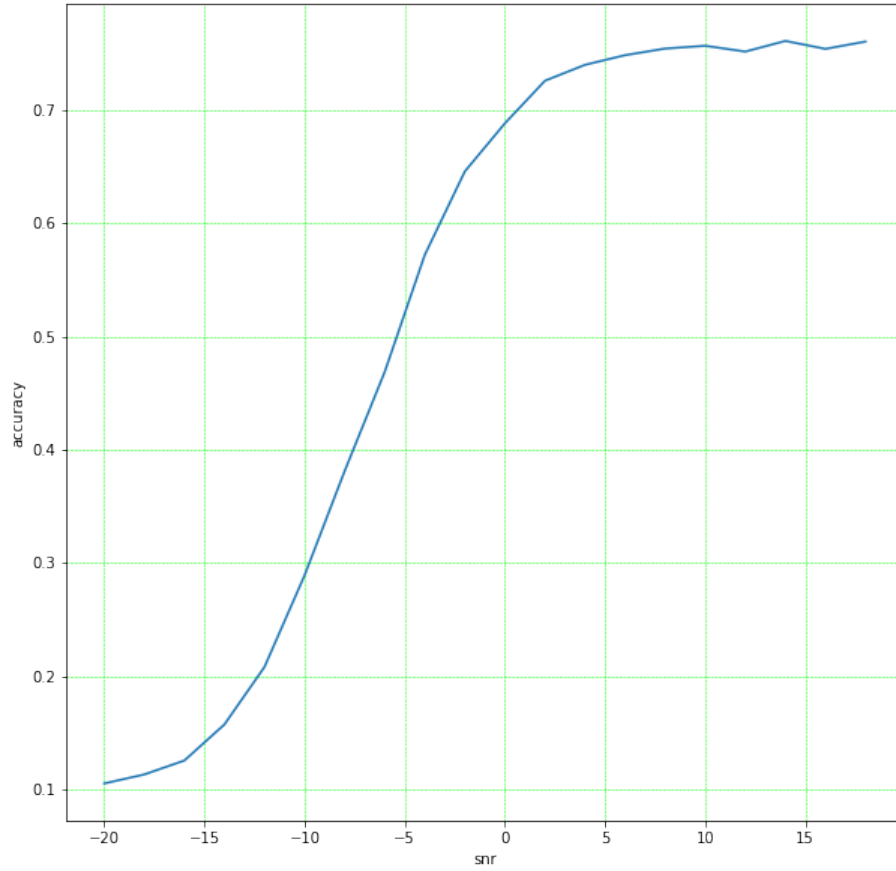


Figure 8: Accuracy vs SNR plot of the Vanilla RNN Model.

- The results at SNR=0dB is **68.79%**

4.3 LSTM Model

4.3.1 Feature Space

Table 5 shows the training and validation accuracy after 8 epochs, for 3 different combinations of features with Adam optimizer with learning rate of 0.001. The raw and integral in time features combination has the best results. Learning rate decay of $1e-6$ is used to avoid sudden decay in accuracy.

features combination	training accuracy	validation accuracy
raw time series	0.6174	0.6202
raw time series integral in time	0.6242	0.6275
raw time series First derivative in time	0.6118	0.6141

Table 5: Comparing different features combinations.

4.3.2 Model Structure

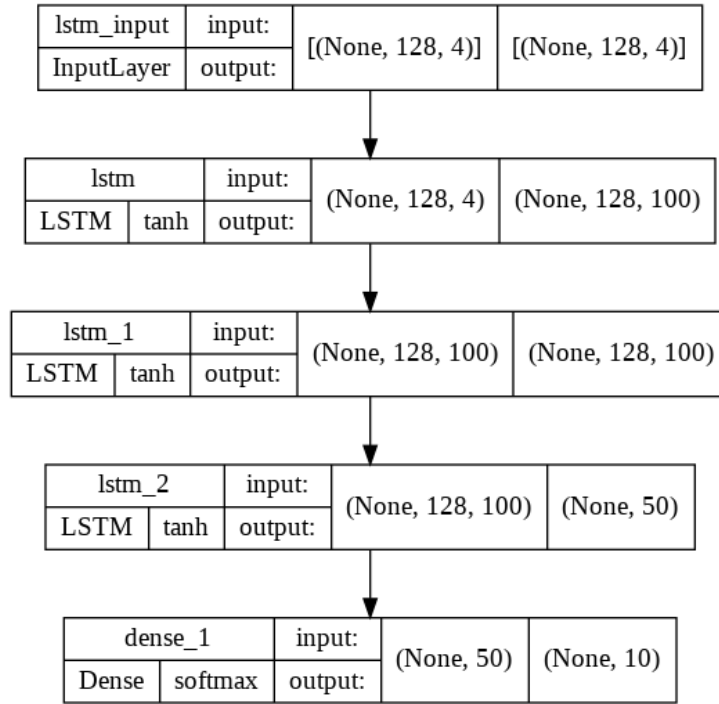


Figure 9: LSTM Model

4.3.3 Learning Rate Tuning

Table 6 shows validation accuracy of different learning rates for Adam optimizer. The raw time series and integral in time features (4 channels) are used. To avoid sudden decay in training and validation accuracy, a learning rate decay of $1e-6$ is applied to the optimizer.

epoch	lr = 0.001	lr = 0.005	lr = 0.0001	lr = 0.0003
1	0.5328	0.5580	0.3990	0.4705
2	0.5671	0.5750	0.4873	0.5070
3	0.5814	0.5919	0.5021	0.5419
4	0.6014	0.6069	0.5149	0.5624
5	0.6124	0.6134	0.5312	0.5678
6	0.6157	0.6201	0.5427	0.5732
7	0.6186	0.6087	0.5504	0.5728
8	0.6246	0.6249	0.5548	0.5740
9	0.6242	0.1000	0.5670	0.5780
10	0.6269	0.1000	0.5693	0.5795
11	0.6264	0.1000	0.5734	0.5856
12	0.6325	0.1000	0.5750	0.5865
13	0.6311	-	0.5786	0.5955
14	0.6323	-	-	0.6032
15	0.6300	-	-	0.6110

Table 6: Tuning results of different learning rates on LSTM model with raw and integral in time features.

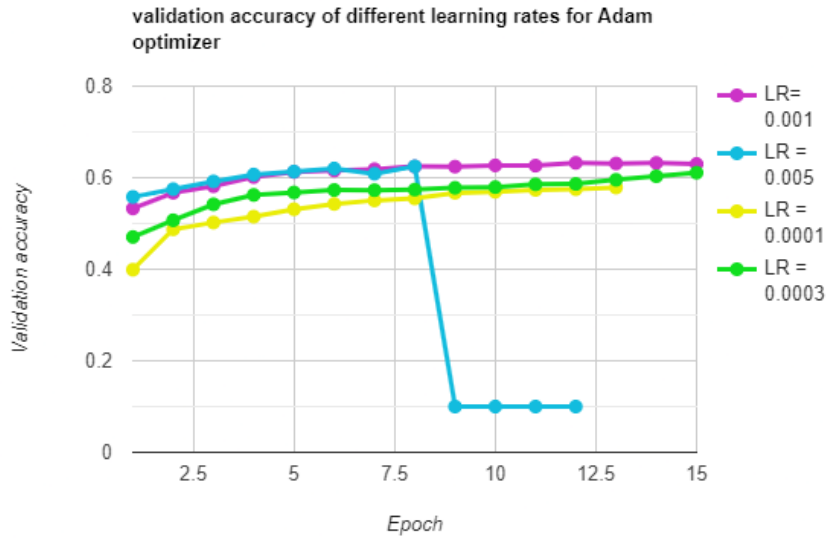


Figure 10: Learning rate plot of LSTM model with raw data with integral in time features.

4.3.4 Training

The final model has the following characteristics:

- Adam optimizer with learning rate = 0.001
- Training accuracy = **65.26%** after 24 epochs
- Validation accuracy = **63.38%**
- Trained with raw time series + integral in time features

4.3.5 Big Picture

- The model has an overall accuracy : **63.31%**
- Overall confusion matrix:

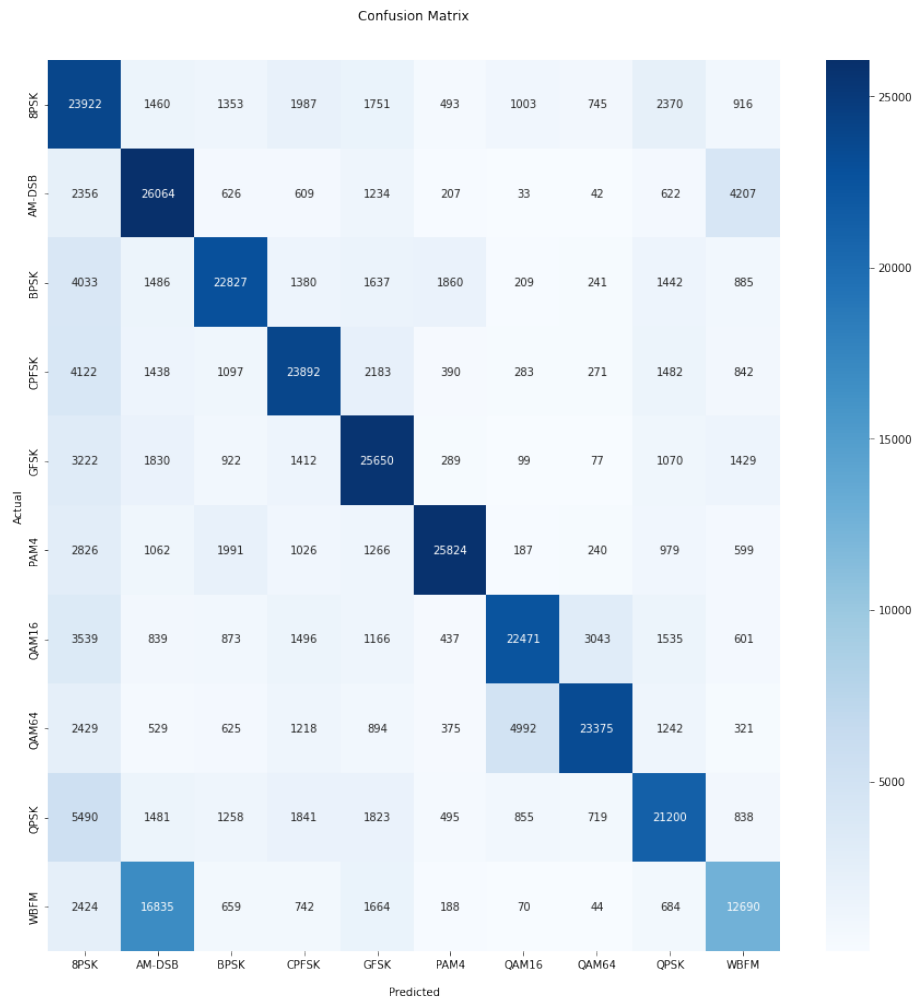


Figure 11: Confusion matrix of the LSTM model.

- The classes AM-DSB and WBFM are usually confused together.
- Accuracy against the SNR :

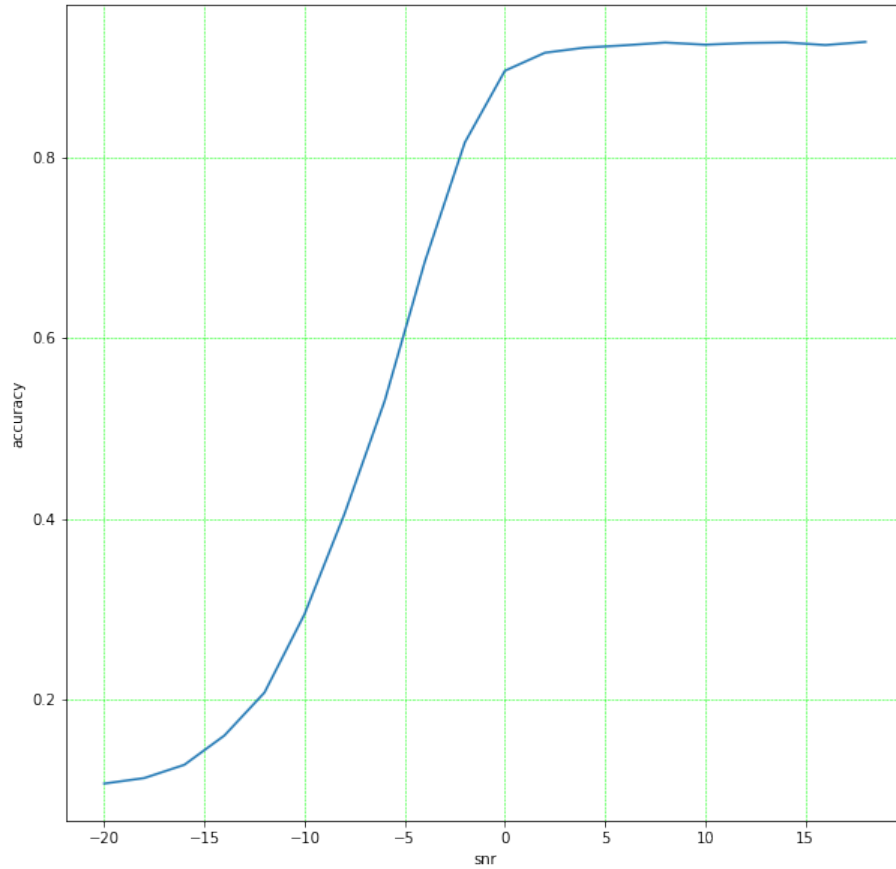


Figure 12: Accuracy vs SNR plot of the LSTM model.

- The results at SNR = 0dB is **89.59%**

4.4 Conv-LSTM Model (Bonus)

4.4.1 Feature Space

Table 7 shows the training and validation accuracy after 10 epochs, for 3 different combinations of features with Adam optimizer with learning rate of 0.001 with decay = $1e-6$. The raw + integral and raw + differentiation have very close results. The raw time series and integral in time is chosen for training.

features combination	training accuracy	validation accuracy
raw time series	0.5263	0.5233
raw time series integral in time	0.5443	0.5392
raw time series First derivative in time	0.5444	0.5413

Table 7: Comparing different features combinations.

4.4.2 Model Structure

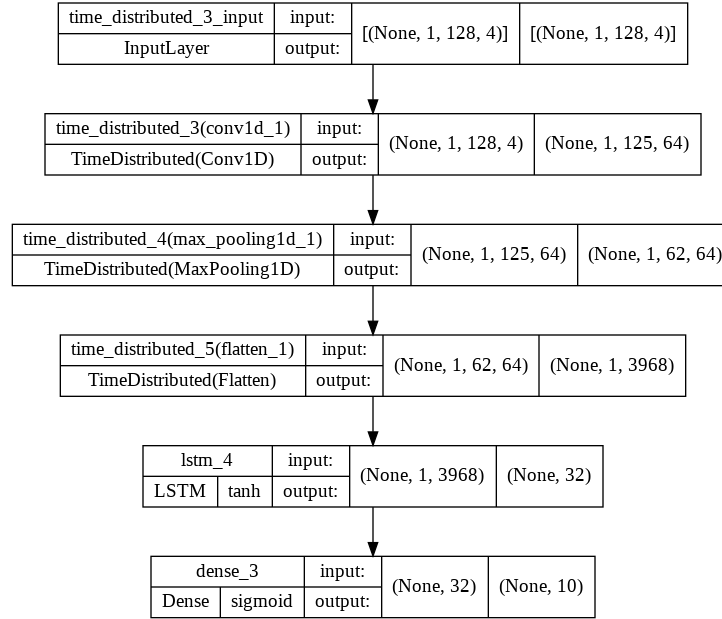


Figure 13: Conv-LSTM Model

4.4.3 Learning Rate Tuning

Table 8 shows validation accuracy of different learning rates for Adam optimizer. The raw time series and integral in time features (4 channels) are used. To avoid sudden decay in training and validation accuracy, a learning rate decay of $1e-6$ is applied to the optimizer.

epoch	lr = 0.001	lr = 0.005	lr = 0.0001	lr = 0.0003
1	0.4944	0.4662	0.3322	0.3965
2	0.5134	0.4733	0.3615	0.4771
3	0.5204	0.4700	0.4150	0.5045
4	0.5254	0.4857	0.4669	0.5105
5	0.5310	0.4908	0.4812	0.5187
6	0.5341	0.4797	0.4897	0.5247
7	0.5339	0.4881	0.4897	0.5292
8	0.5352	0.4830	0.5011	0.5321
9	0.5368	0.4867	0.5039	0.5356
10	0.5378	0.4918	0.5007	0.5411

Table 8: Tuning results of different learning rates on Conv-LSTM model with raw and integral in time features.

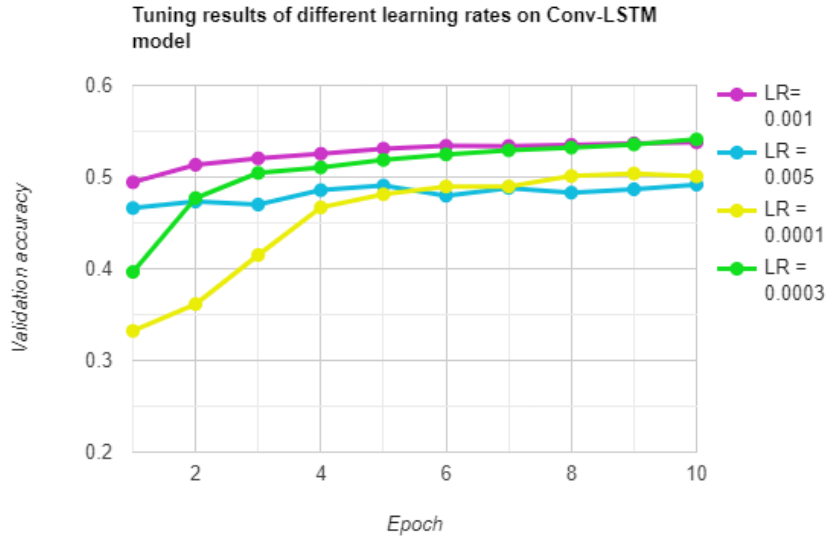


Figure 14: Learning rate plot of LSTM model with raw data with integral in time features.

4.4.4 Training

The final model has the following characteristics:

- Adam optimizer with learning rate = 0.0003
- Training accuracy = 56.38% after 32% epochs
- Trained with raw time series + integral in time features

- Validation accuracy = **54.79%**

4.4.5 Big Picture

- The model has an overall accuracy : **53.866%**
- Overall confusion matrix:

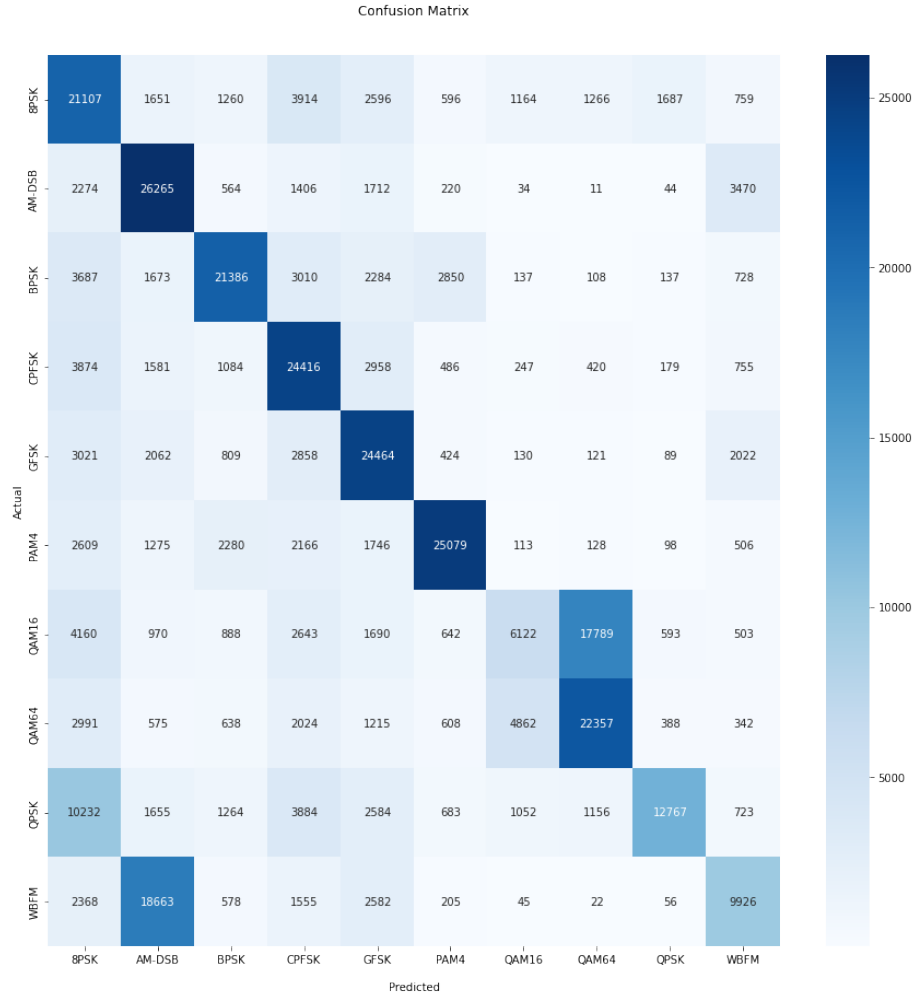


Figure 15: Confusion matrix of the Conv-LSTM model.

- The most confusing classes are (AM-DSB with WBFM), (8PSK with QPSK). QAM16 and QAM64 are usually predicted as QAM64.

- Accuracy against the SNR :

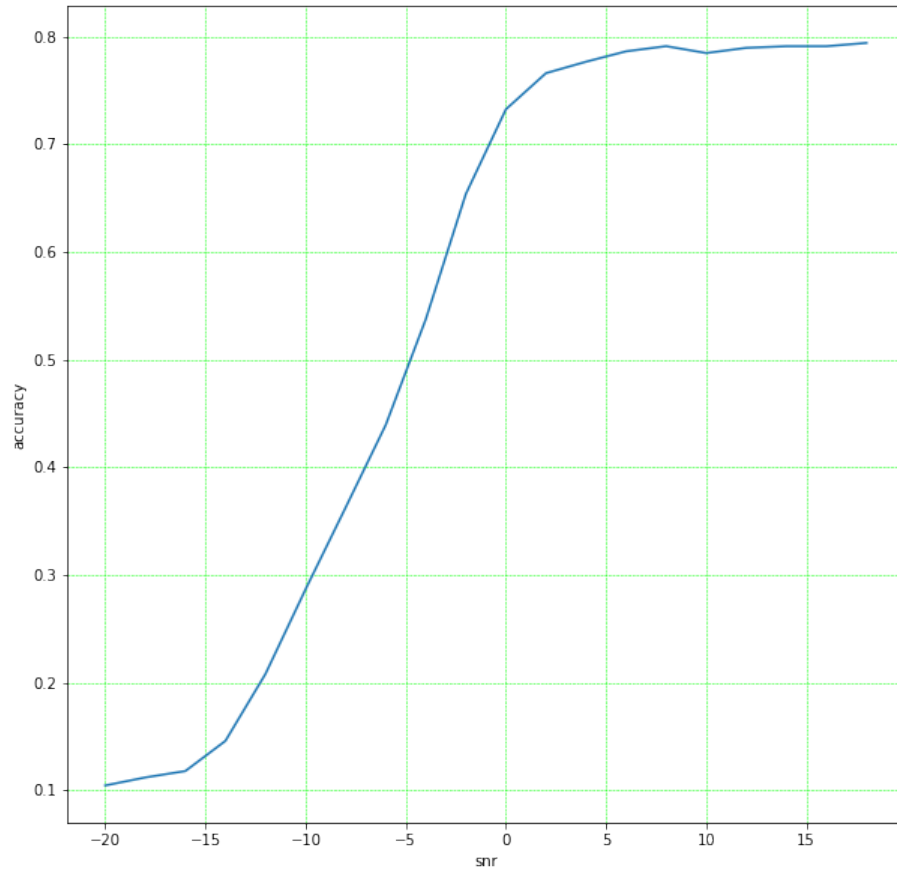


Figure 16: Accuracy vs SNR plot of the Conv-LSTM model.

- The results at SNR=0dB is **89.594%**

5 Summary

The model with the highest accuracy and least confusing classing is the LSTM model, trained with raw data with integral in time features. It achieved 63.31% testing accuracy.

6 Colab Notebook

[Link](#)