classification_models (1)

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1 Importing packages

[3]:
```
import pickle
import os
import pandas as pd
import numpy as np
import seaborn as sns
import matplotlib.pyplot as plt
from scipy import integrate
from sklearn.metrics import confusion_matrix
from sklearn.model_selection import train_test_split
from sklearn.preprocessing import normalize
from tensorflow.keras.models import Sequential
from tensorflow.keras.layers import Dense, Dropout, Activation, Flatten, Conv1D,␣
↪MaxPool1D, Conv2D, MaxPool2D,BatchNormalization, GRU
from tensorflow.keras.optimizers import Adam
from sklearn import metrics
import tensorflow as tf
from sklearn.preprocessing import OneHotEncoder
from tensorflow.keras.callbacks import ModelCheckpoint
from sklearn.preprocessing import OneHotEncoder
from keras.layers import LSTM
from keras.layers.embeddings import Embedding
from keras.layers import SimpleRNN
from sklearn.metrics import accuracy_score
```

2 1. Download the Dataset

[4]:
```
from google.colab import drive
drive.mount('/content/drive')
```

```
Drive already mounted at /content/drive; to attempt to forcibly remount, call
drive.mount("/content/drive", force_remount=True).
```

[5]:
```
import os
os.chdir('/content/drive/MyDrive/RML2016_dataset/')
Data = pickle.load(open("RML2016.10b.dat",'rb'), encoding = 'bytes')
snrs, mods = map(lambda j: sorted(list(set(map(lambda x: x[j], Data.keys())))),␣
 ↪[1,0])
```

[6]:
```
print(f"Mods: {mods}")
print(f"SNRs: {snrs}")
```

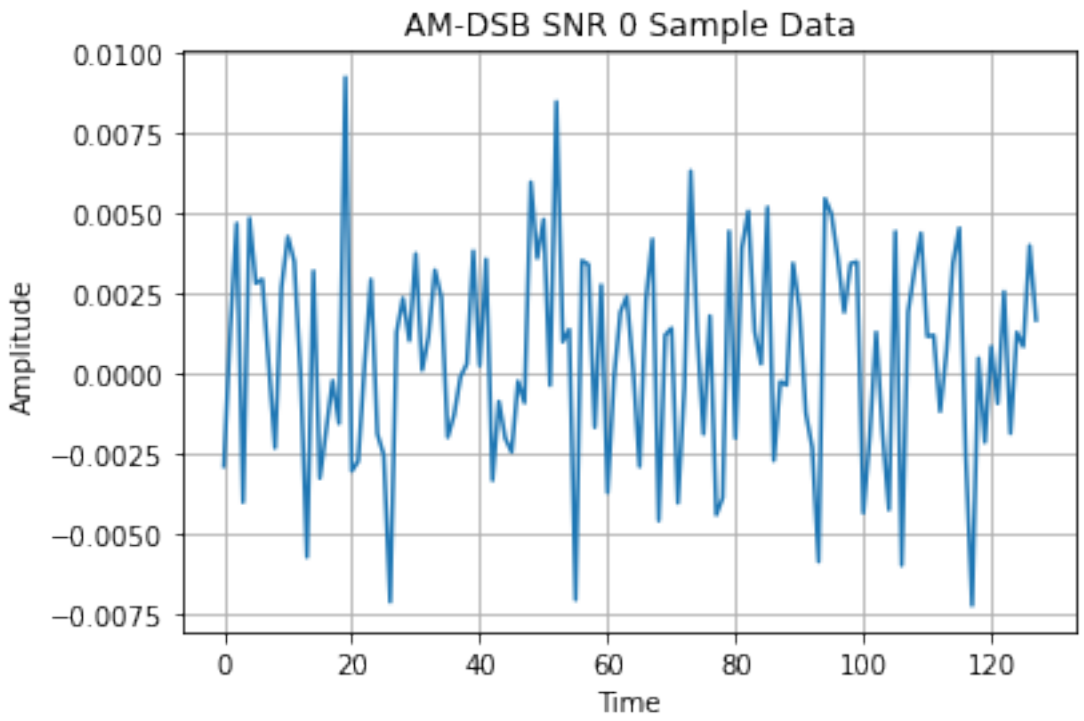
```
Mods: [b'8PSK', b'AM-DSB', b'BPSK', b'CPFSK', b'GFSK', b'PAM4', b'QAM16',
b'QAM64', b'QPSK', b'WBFM']
SNRs: [-20, -18, -16, -14, -12, -10, -8, -6, -4, -2, 0, 2, 4, 6, 8, 10, 12, 14,
16, 18]
```

[7]:
```
samples = []
snr_mod_labels = []
for snr in snrs:
  x = []
  y = []
  curr_snr_labels = []
  for mod in mods:
    x.append(Data[(mod,snr)])
    y.append([mod] * Data[(mod,snr)].shape[0])
    curr_snr_labels.append([snr, mod] * Data[(mod,snr)].shape[0])
  y = np.array(y)
  curr_snr_labels = np.array(curr_snr_labels)
  snr_mod_labels.append(curr_snr_labels.reshape((int(curr_snr_labels.shape[1]/2)␣
 ↪* curr_snr_labels.shape[0], 2)))
  samples.append(np.vstack(x))

samples = np.array(samples)
snr_mod_labels = np.array(snr_mod_labels)
```

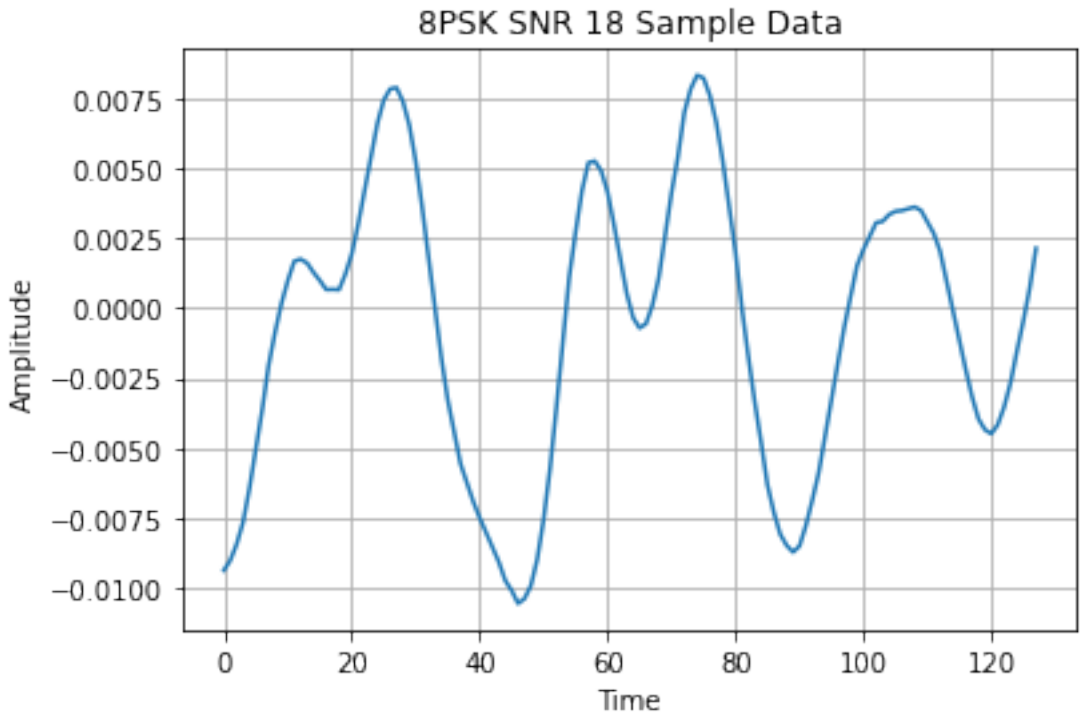
[8]:
```
print(samples.shape)
print(snr_mod_labels.shape)
```

```
(20, 60000, 2, 128)
(20, 60000, 2)
```

[9]:
```
plt.plot(Data[b'AM-DSB',0][2,0])
plt.xlabel("Time")
plt.ylabel("Amplitude")
plt.title("AM-DSB SNR 0 Sample Data")
plt.grid(b=True, axis='both')
```



[10]:
```
plt.plot(Data[b'8PSK',18][2,0])
plt.xlabel("Time")
plt.ylabel("Amplitude")
plt.title("8PSK SNR 18 Sample Data")
plt.grid(b=True, axis='both')
```



3 General functions

[11]:
```
def reshape_data_for_cnn(tr_data, val_data, tst_data):
  tr_data = tr_data.reshape((tr_data.shape[0], tr_data.shape[1], tr_data.
 ↪shape[2], 1))
  val_data = val_data.reshape((val_data.shape[0], val_data.shape[1], val_data.
 ↪shape[2], 1))
  tst_data = tst_data.reshape((tst_data.shape[0], tst_data.shape[1], tst_data.
 ↪shape[2], 1))

  return tr_data, val_data, tst_data
```

[12]:
```
def reshape_data_for_rnn_lstm(tr_data, val_data, tst_data):
  tr_data = tr_data.reshape(tr_data.shape[0], tr_data.shape[1], tr_data.shape[2])
  val_data = val_data.reshape(val_data.shape[0], val_data.shape[1], val_data.
 ↪shape[2])
  tst_data = tst_data.reshape(tst_data.shape[0], tst_data.shape[1], tst_data.
 ↪shape[2])

  return tr_data, val_data, tst_data
```

4 Data Splitting And Balancing

[13]:
```
#Reshaping dataset
samples = samples.reshape((samples.shape[0] * samples.shape[1], samples.
 ↪shape[2], samples.shape[3]))
labels = snr_mod_labels.reshape((-1, 2)) # Notic that the labels are at this␣
 ↪format [snr, modulation]
```

[14]:
```
print('samples shape:', samples.shape)
print('labels shape:', labels.shape)
```

```
samples shape: (1200000, 2, 128)
labels shape: (1200000, 2)
```

[15]:
```
#Splitting data
training_val_data, testing_data, training_val_pair_labels, testing_pair_labels =␣
 ↪train_test_split(samples, labels,stratify=labels, shuffle=True, test_size=0.3)
training_data, validation_data, training_pair_labels, validation_pair_labels = ␣
 ↪train_test_split(training_val_data,␣
 ↪training_val_pair_labels,stratify=training_val_pair_labels, shuffle=True,␣
 ↪test_size=0.05)
```

[16]:
```
del samples
```

[17]:
```
training_labels = training_pair_labels[:, 1]
validation_labels = validation_pair_labels[:, 1]
```

[18]:
```
print('training data shape:', training_data.shape)
print('training labels shape:', training_labels.shape)
print('validation data shape:', validation_data.shape)
print('validation labels shape:', validation_labels.shape)
print('testing data shape:', testing_data.shape)
print('testing labels shape:', testing_pair_labels.shape)
```

```
training data shape: (798000, 2, 128)
training labels shape: (798000,)
validation data shape: (42000, 2, 128)
validation labels shape: (42000,)
testing data shape: (360000, 2, 128)
testing labels shape: (360000, 2)
```

[19]:
```
unique, counts = np.unique(training_labels, return_counts=True)
print('training:\t', dict(zip(unique, counts)))
unique, counts = np.unique(validation_labels, return_counts=True)
print('validation:\t', dict(zip(unique, counts)))
unique, counts = np.unique(testing_pair_labels, return_counts=True)
print('testing:\t', dict(zip(unique, counts)))
```

```
training:        {b'8PSK': 79800, b'AM-DSB': 79800, b'BPSK': 79800, b'CPFSK':
79800, b'GFSK': 79800, b'PAM4': 79800, b'QAM16': 79800, b'QAM64': 79800,
b'QPSK': 79800, b'WBFM': 79800}
validation:      {b'8PSK': 4200, b'AM-DSB': 4200, b'BPSK': 4200, b'CPFSK': 4200,
b'GFSK': 4200, b'PAM4': 4200, b'QAM16': 4200, b'QAM64': 4200, b'QPSK': 4200,
b'WBFM': 4200}
testing:         {b'-10': 18000, b'-12': 18000, b'-14': 18000, b'-16': 18000,
b'-18': 18000, b'-2': 18000, b'-20': 18000, b'-4': 18000, b'-6': 18000, b'-8':
18000, b'0': 18000, b'10': 18000, b'12': 18000, b'14': 18000, b'16': 18000,
b'18': 18000, b'2': 18000, b'4': 18000, b'6': 18000, b'8': 18000, b'8PSK':
36000, b'AM-DSB': 36000, b'BPSK': 36000, b'CPFSK': 36000, b'GFSK': 36000,
b'PAM4': 36000, b'QAM16': 36000, b'QAM64': 36000, b'QPSK': 36000, b'WBFM':
36000}
```

[20]:
```
# converting labels to one hot encoding
training_onehot = OneHotEncoder(sparse = False).fit_transform(training_labels.
 ↪reshape(-1,1))
validation_onehot = OneHotEncoder(sparse = False).
 ↪fit_transform(validation_labels.reshape(-1,1))
```

[21]:
```
print('training onehot encoding shape:', training_onehot.shape)
print('validation onehot encoding shape:', validation_onehot.shape)
```

```
training onehot encoding shape: (798000, 10)
validation onehot encoding shape: (42000, 10)
```

5 Scoring functions

[22]:
```
def model_pred_and_accuracy(model, testing_data, testing_labels):
  pred = model.predict(testing_data)
  decoded_pred = np.argmax(pred, axis=1)
  testing_labels = np.argmax(testing_labels, axis=1)

  return pred, accuracy_score(testing_labels, decoded_pred)
```

[23]:
```
def confusion_matrixf(pred, actual, title):
  actual_decode = np.argmax(actual, axis=1)
  pred_decode = np.argmax(pred, axis=1)
  confusion_mtx = confusion_matrix(actual_decode, pred_decode)
  plt.figure(figsize=(10, 8))
  sns.heatmap(confusion_mtx, xticklabels=mods, yticklabels=mods, annot=True,␣
 ↪fmt='g')
  plt.xlabel('Prediction')
  plt.ylabel('Actual')
  plt.title(title)
  plt.show()
```

[24]:
```
def plot_model_history(history, title=''):
  pd.DataFrame(history.history).plot(figsize=(8,5))
  plt.title(title)
  plt.show()
```

[25]:
```
def plot_snr_vs_acc(snr, acc):
  plt.plot(snr, acc, label = "SNR vs Accuracy")
  plt.xlabel('SNR')
  plt.ylabel('Accuracy')
  plt.legend()
  plt.show()
```

[26]:
```
def model_scoring(model, history, testing_data, testing_pair_labels):
  sorted_idx = testing_pair_labels[:, 0].astype(int).argsort() # sort by snr␣
 ↪value
  testing_data = testing_data[sorted_idx] # to sort samples by snr
  testing_pair_labels = testing_pair_labels[sorted_idx] # to sort labels by snr

  SNRs = testing_pair_labels[:, 0]
  modulations = testing_pair_labels[:, 1]
  unique_snr, snr_count = np.unique(SNRs, return_counts=True)
  snr_count_dict = dict(zip(unique, counts))

  curr_sample = 0
  snr = []
  acc = []
  for i in range(len(unique_snr)):
    curr_snr = SNRs[curr_sample]
    curr_snr_samples = []
    curr_snr_labels = []
    for j in range(snr_count_dict[curr_snr]):
      curr_snr_samples.append(testing_data[curr_sample])
      curr_snr_labels.append(modulations[curr_sample])
      curr_sample += 1

    curr_snr_samples = np.array(curr_snr_samples)
    curr_snr_labels = np.array(curr_snr_labels)
    onehot_labels = OneHotEncoder(sparse = False).fit_transform(curr_snr_labels.
 ↪reshape(-1,1))

    pred, accuracy = model_pred_and_accuracy(model, curr_snr_samples,␣
 ↪onehot_labels)
    snr.append(int(curr_snr.decode()))
    acc.append(accuracy)
    print('Accuracy at SNR = ' + curr_snr.decode() + ' is ' + str(accuracy) +␣
 ↪'%')
    confusion_matrixf(pred, onehot_labels, 'SNR: ' + curr_snr.decode())
```

```
plot_snr_vs_acc(snr, acc)
```

6 Normal Feature Space

6.1 CNN Model

[ ]:
```
training_data, validation_data, testing_data =␣
↪reshape_data_for_cnn(training_data, validation_data, testing_data)
```

[ ]:
```
print('training data shape:', training_data.shape)
print('validation data shape:', validation_data.shape)
print('testing data shape:', testing_data.shape)
```

```
training data shape: (798000, 2, 128, 1)
validation data shape: (42000, 2, 128, 1)
testing data shape: (360000, 2, 128, 1)
```

[ ]:
```
learning_rate = 0.001
batch_size = 512
epochs = 200
```

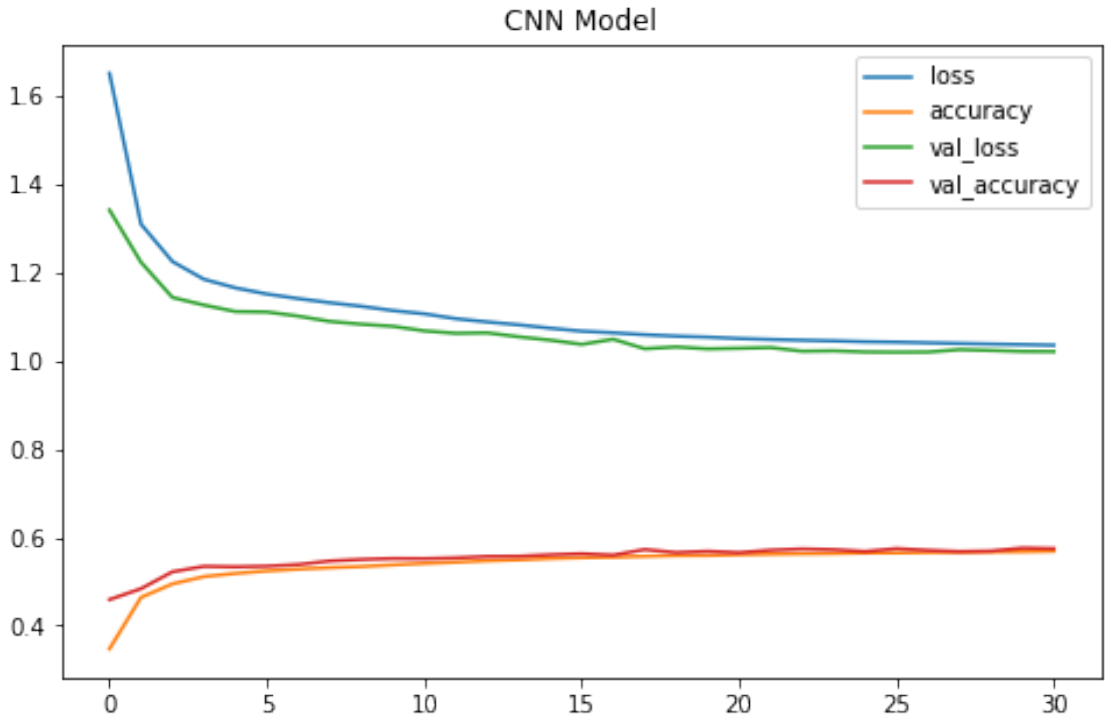
[ ]:
```
cnn_model = Sequential()
cnn_model.add(Conv2D(256, 3, activation='relu', padding='same'))
cnn_model.add(Dropout(0.5))
cnn_model.add(Conv2D(64, 3, strides=2, activation='relu', padding='same'))
cnn_model.add(Dropout(0.5))
cnn_model.add(Flatten())
cnn_model.add(Dense(128, activation='relu' ))
cnn_model.add(Dense(10,  activation='softmax'))
cnn_model.compile(loss=tf.keras.losses.CategoricalCrossentropy(),␣
↪metrics='accuracy', optimizer=tf.keras.optimizers.
↪Adam(learning_rate=learning_rate))
```

[ ]:
```
es = tf.keras.callbacks.EarlyStopping(monitor="val_loss", patience=5,␣
↪restore_best_weights=True,)
checkpointer = ModelCheckpoint(filepath='saved_models/classification.hdf5',␣
↪verbose=1, save_best_only=True)

with tf.device('/device:GPU:0'):
  history = cnn_model.fit(training_data, training_onehot, batch_size=batch_size,␣
↪epochs=epochs, validation_data=(validation_data, validation_onehot),␣
↪callbacks=[es, checkpointer], verbose=1)
```

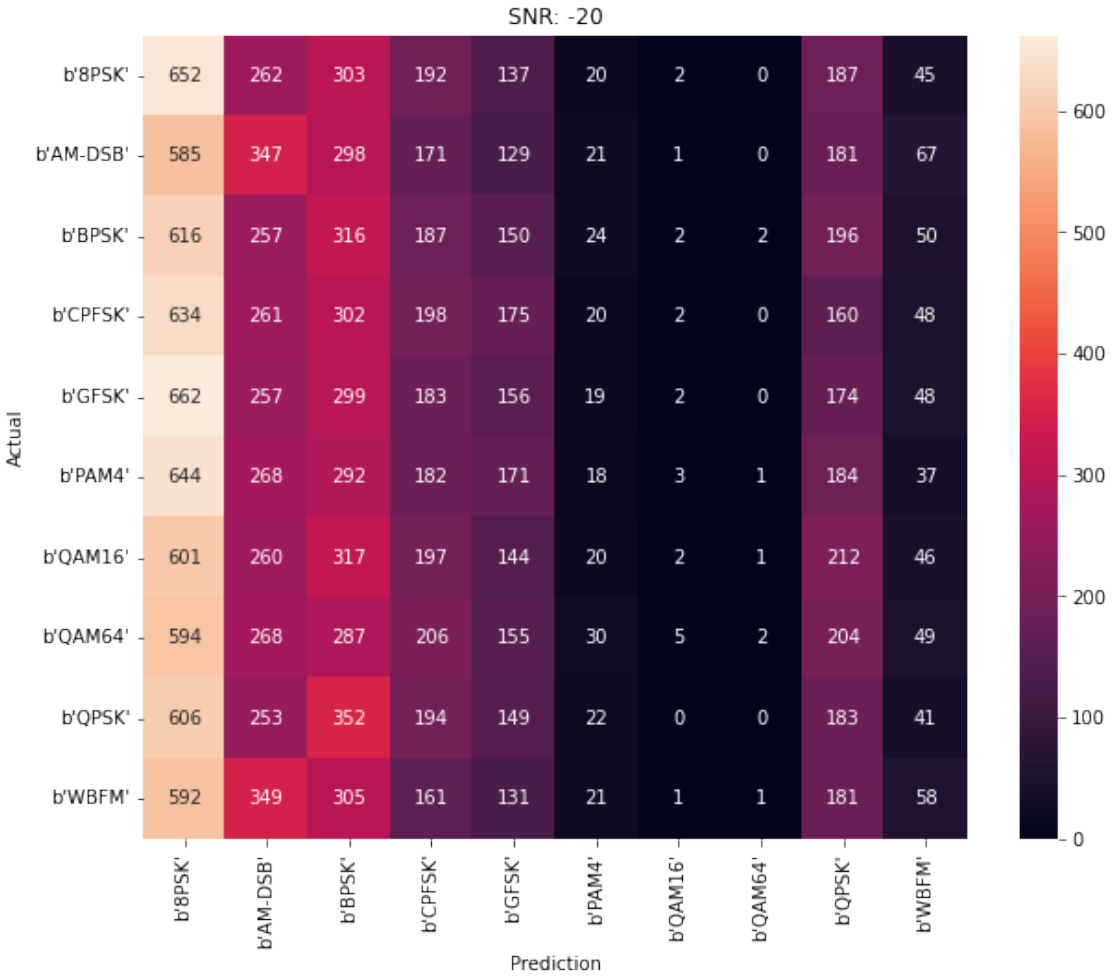
```
Epoch 1/200
1559/1559 [==============================] - ETA: 0s - loss: 1.6489 - accuracy:
0.3475
```

```
Epoch 1: val_loss improved from inf to 1.33986, saving model to
saved_models/classification.hdf5
1559/1559 [==============================] - 77s 41ms/step - loss: 1.6489 -
accuracy: 0.3475 - val_loss: 1.3399 - val_accuracy: 0.4589

Epoch 31: val_loss did not improve from 1.01837
1559/1559 [==============================] - 63s 41ms/step - loss: 1.0342 -
accuracy: 0.5684 - val_loss: 1.0197 - val_accuracy: 0.5741
```

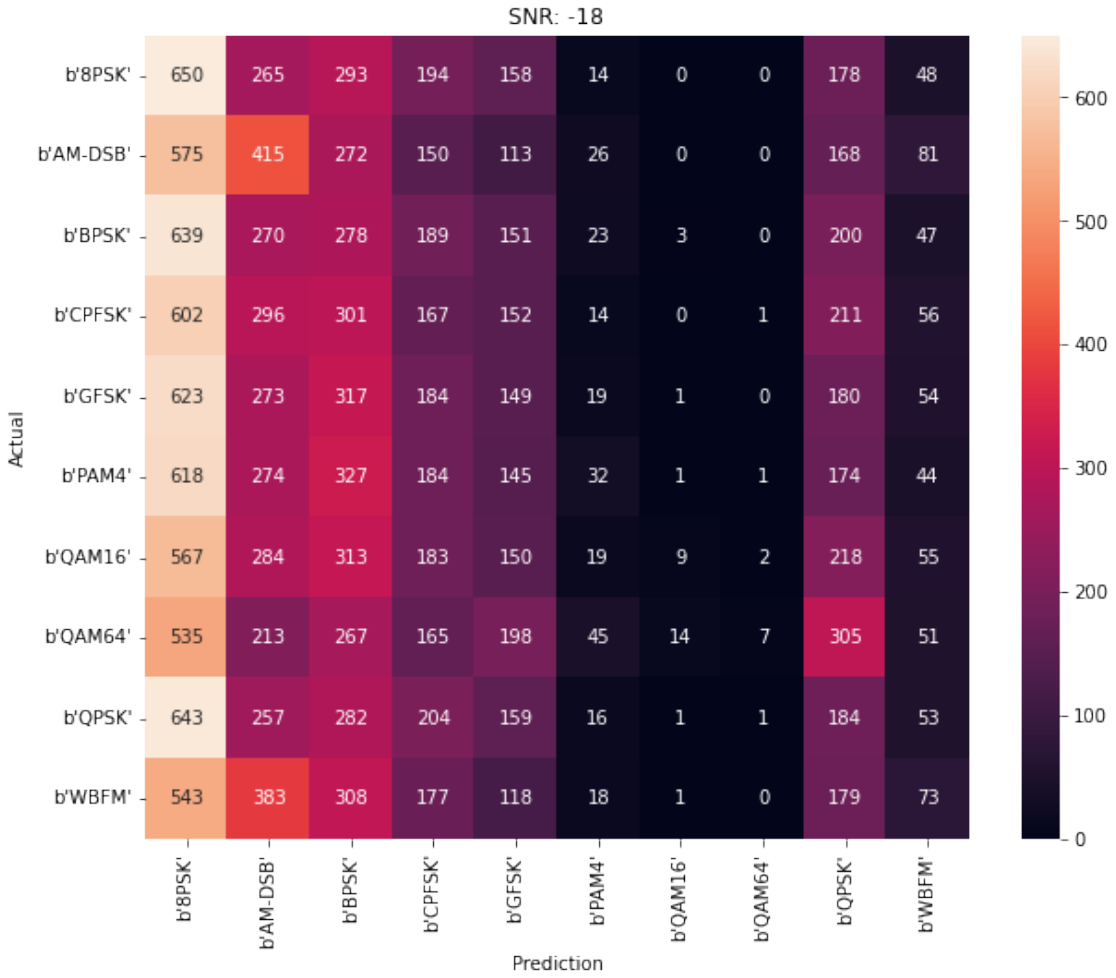
[ ]:
```
plot_model_history(history, 'CNN Model')
model_scoring(cnn_model, history, testing_data, testing_pair_labels)
```



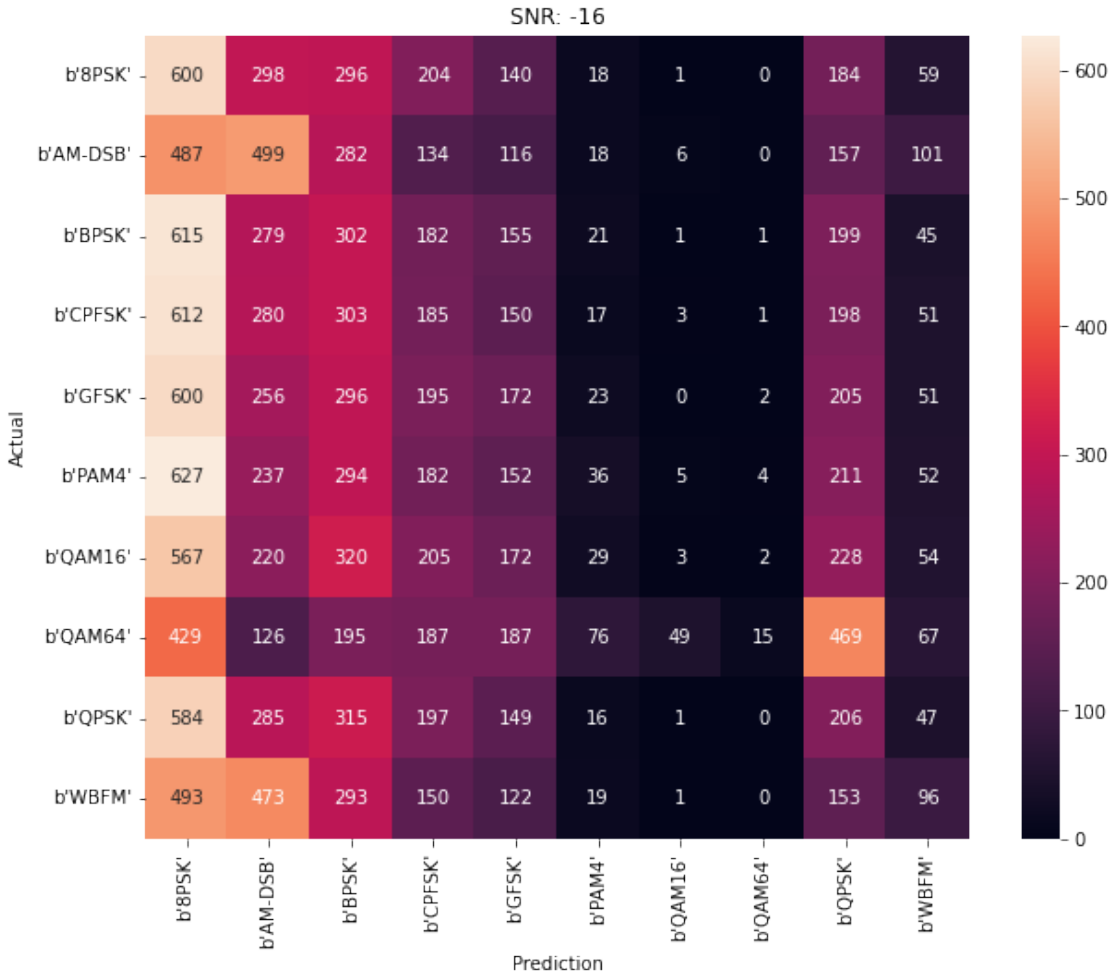

```
Accuracy at SNR = -20 is 0.10733333333333334%
```



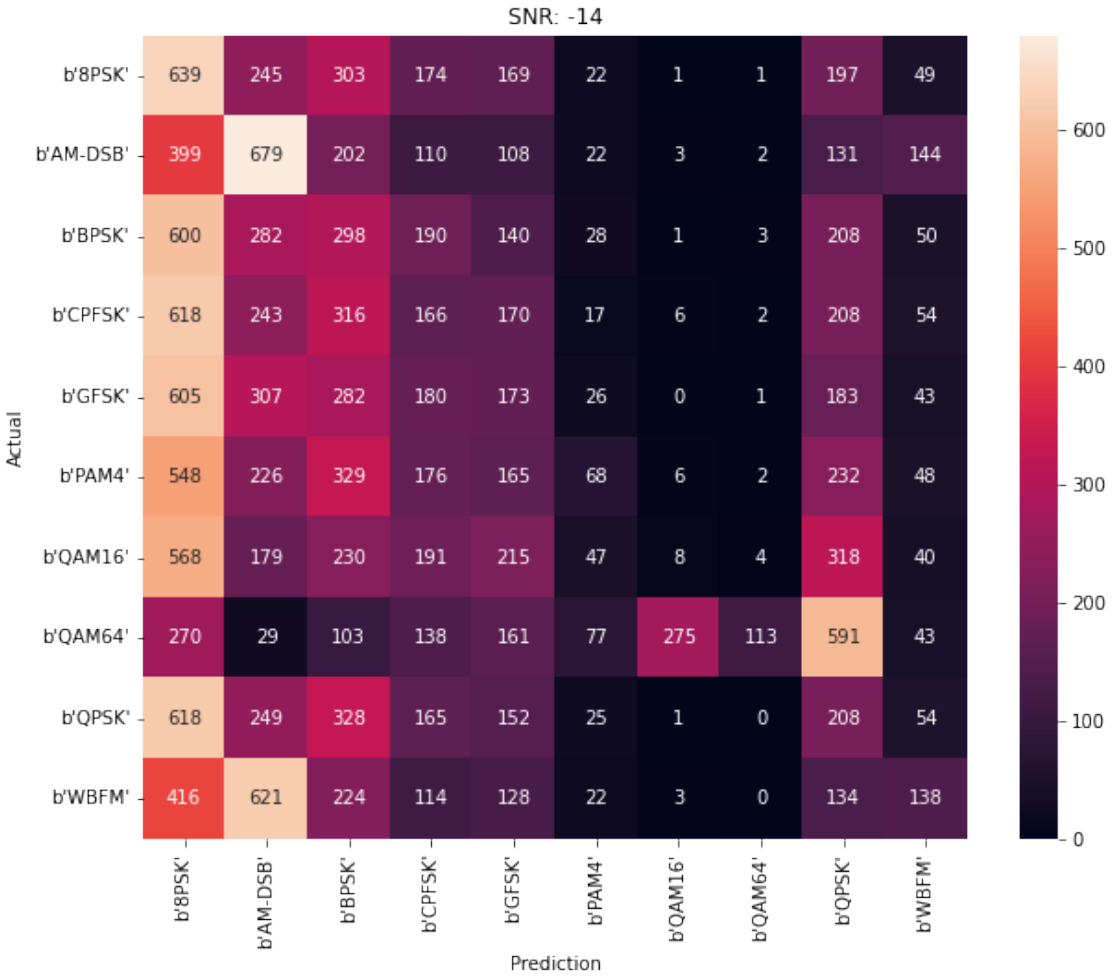

```
Accuracy at SNR = -18 is 0.10911111111111112%
```



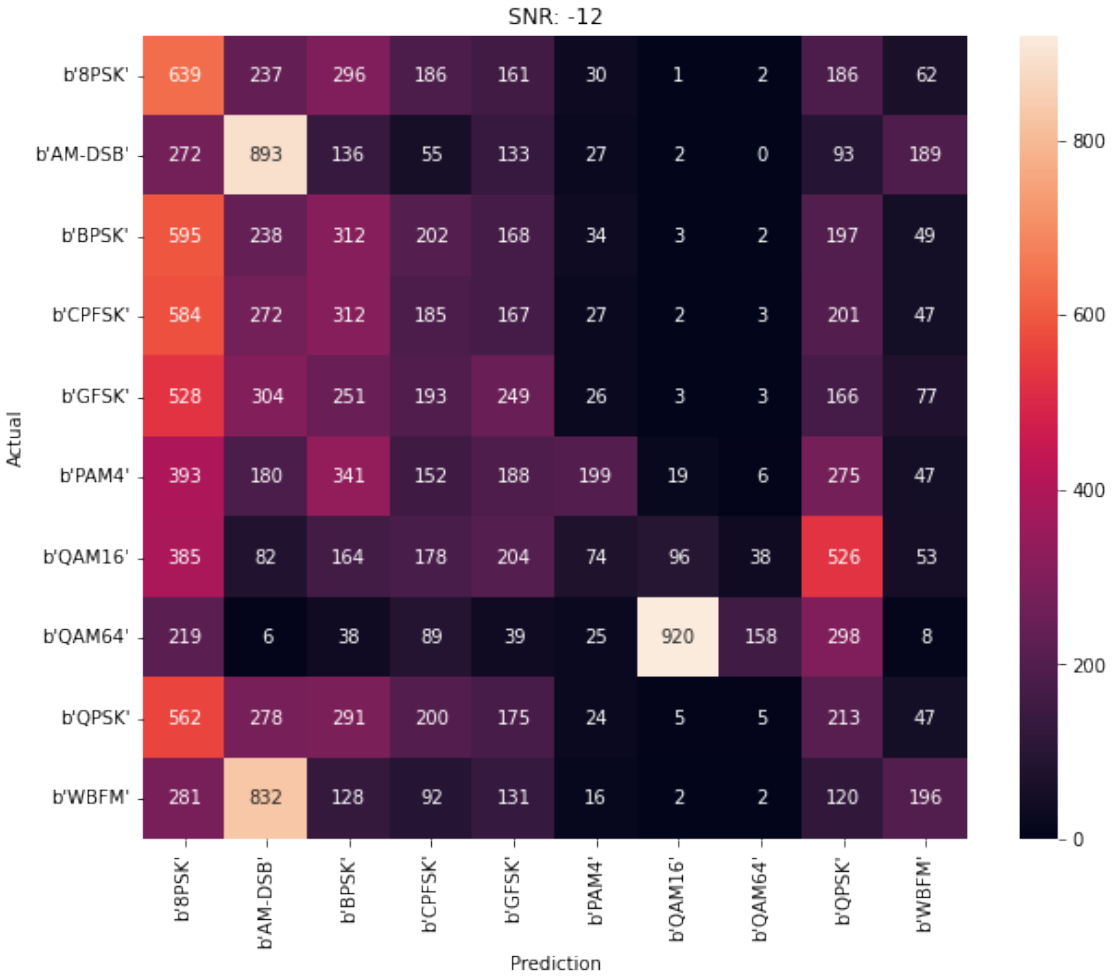

```
Accuracy at SNR = -16 is 0.11744444444444445%
```



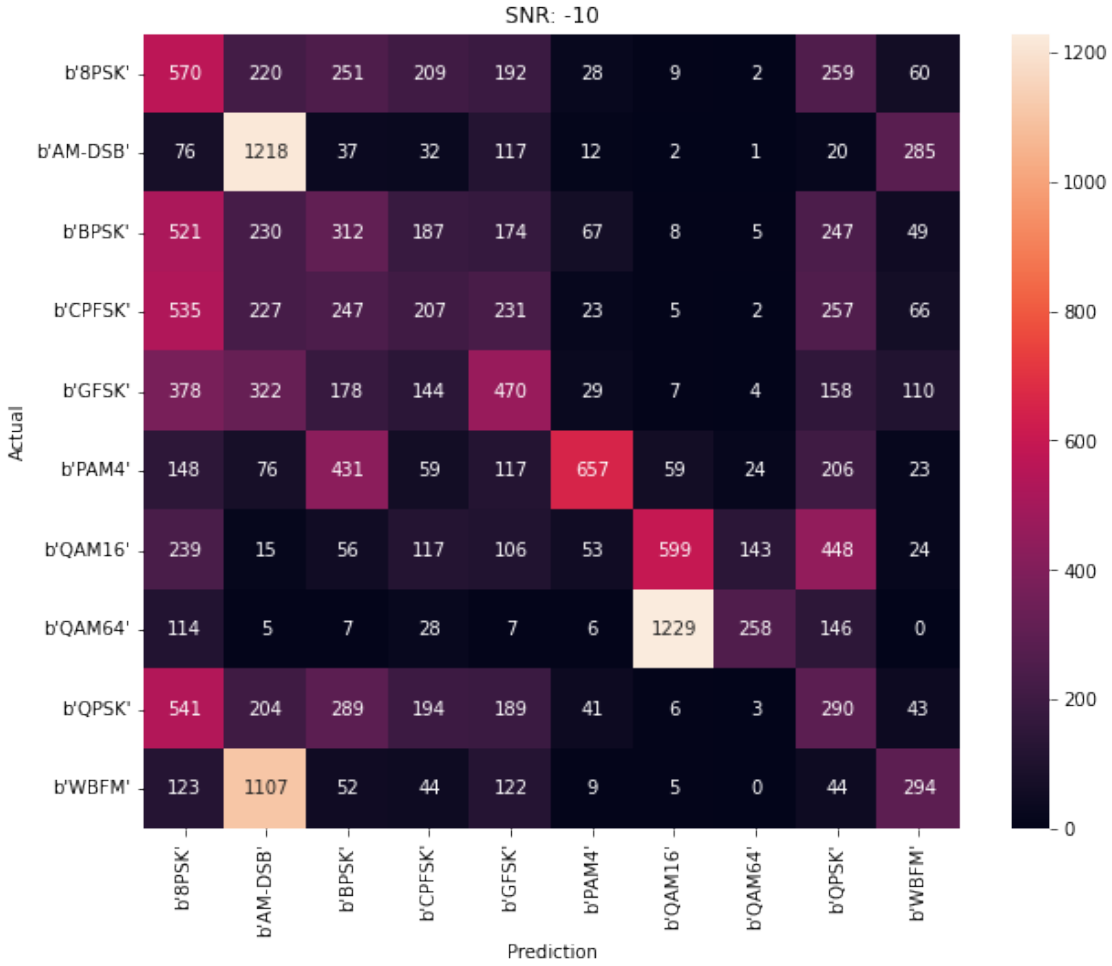
Accuracy at SNR = -14 is 0.13833333333333334%



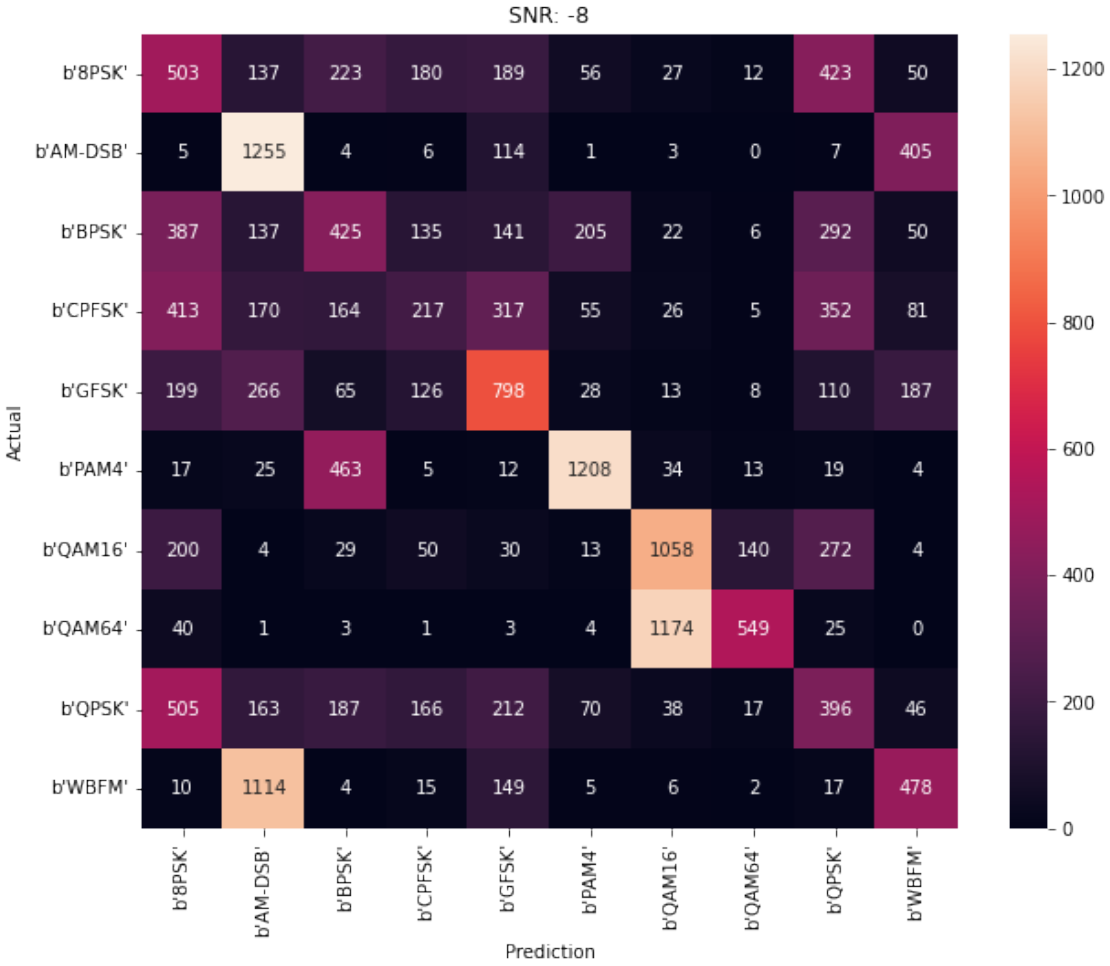

```
Accuracy at SNR = -12 is 0.17444444444444446%
```



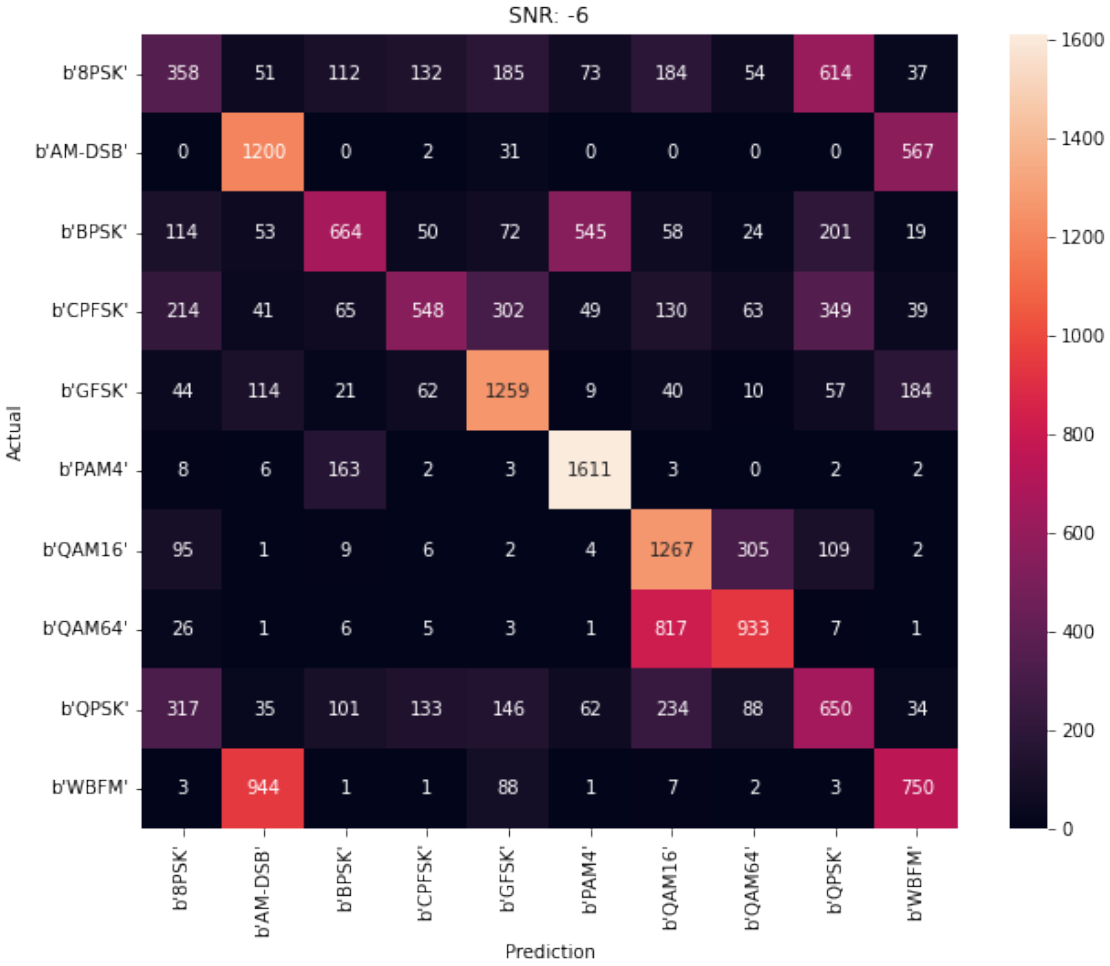
Accuracy at SNR = -10 is 0.2708333333333333%



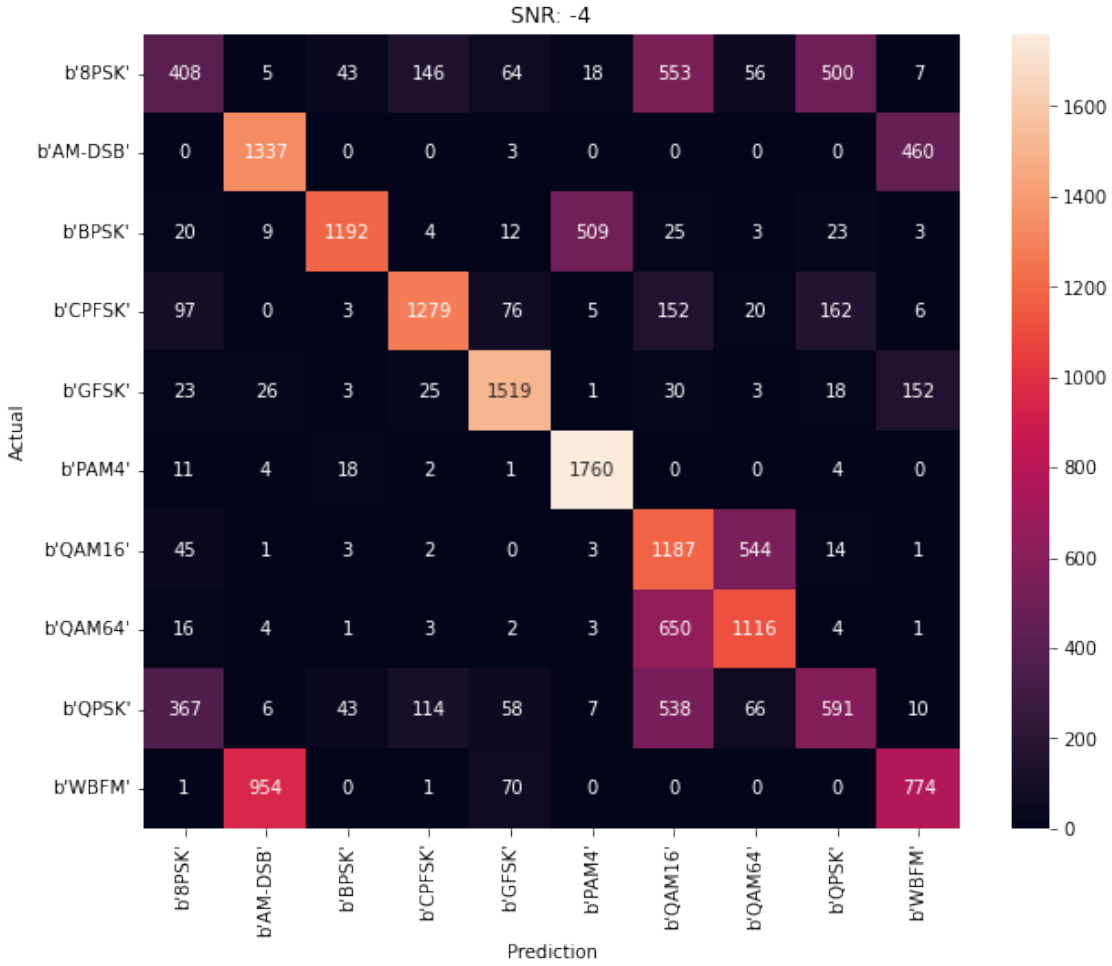
Accuracy at SNR = -8 is 0.3826111111111111%



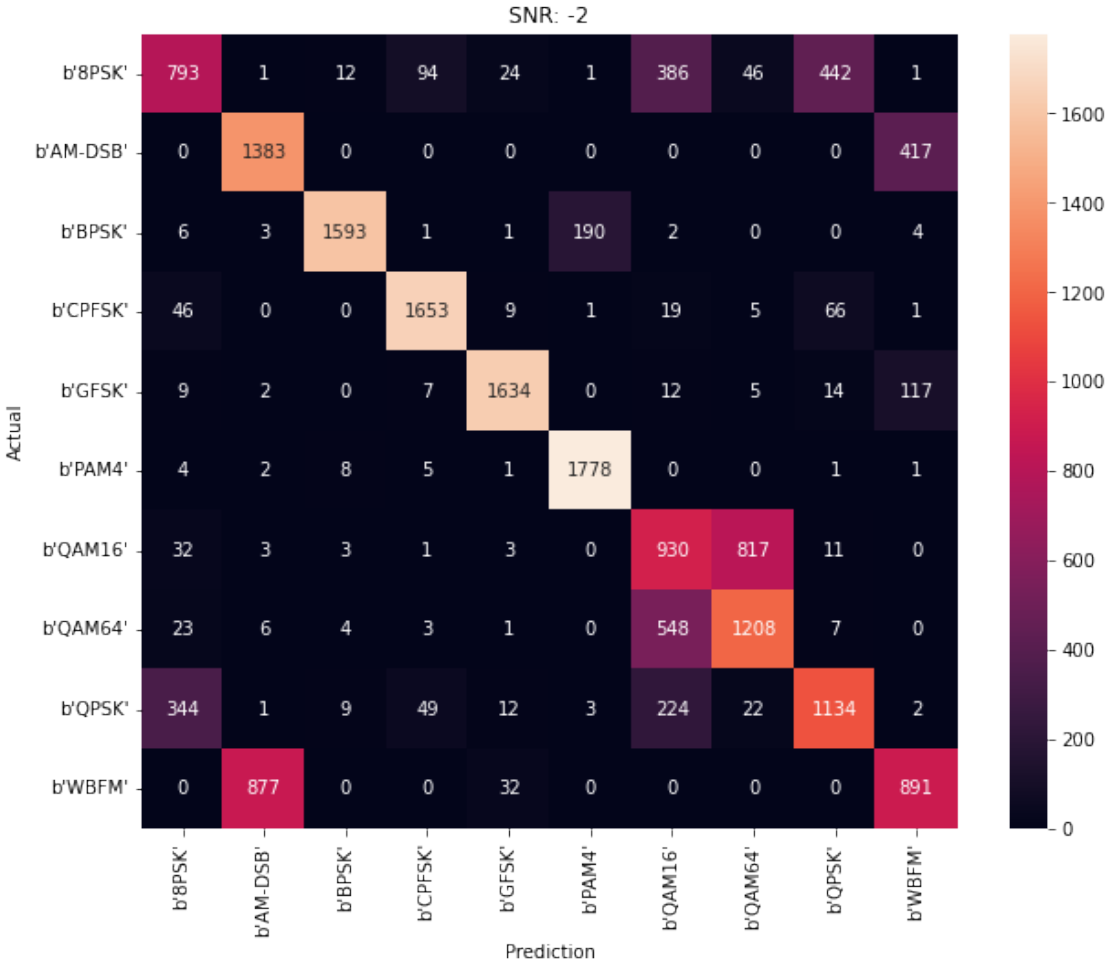

```
Accuracy at SNR = -6 is 0.5133333333333333%
```



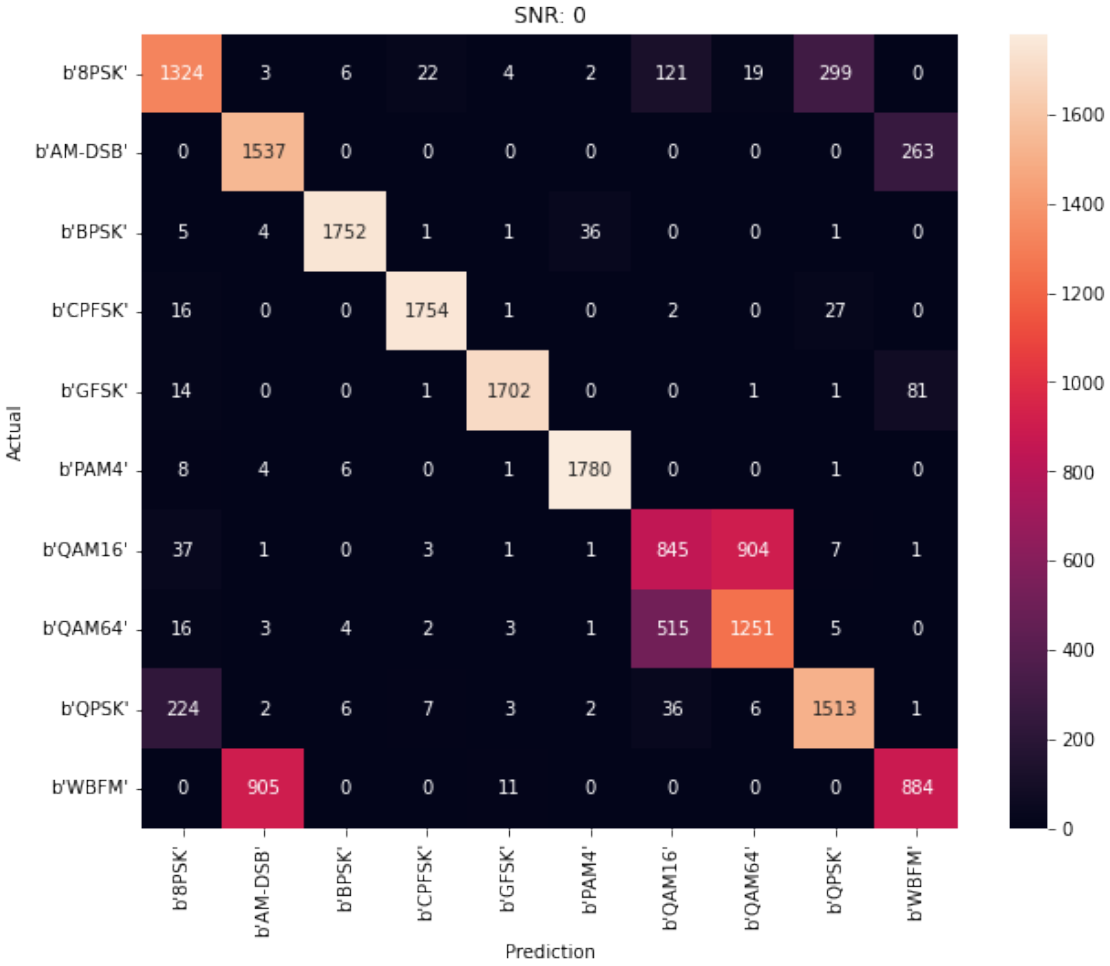
Accuracy at SNR = -4 is 0.6201666666666666%



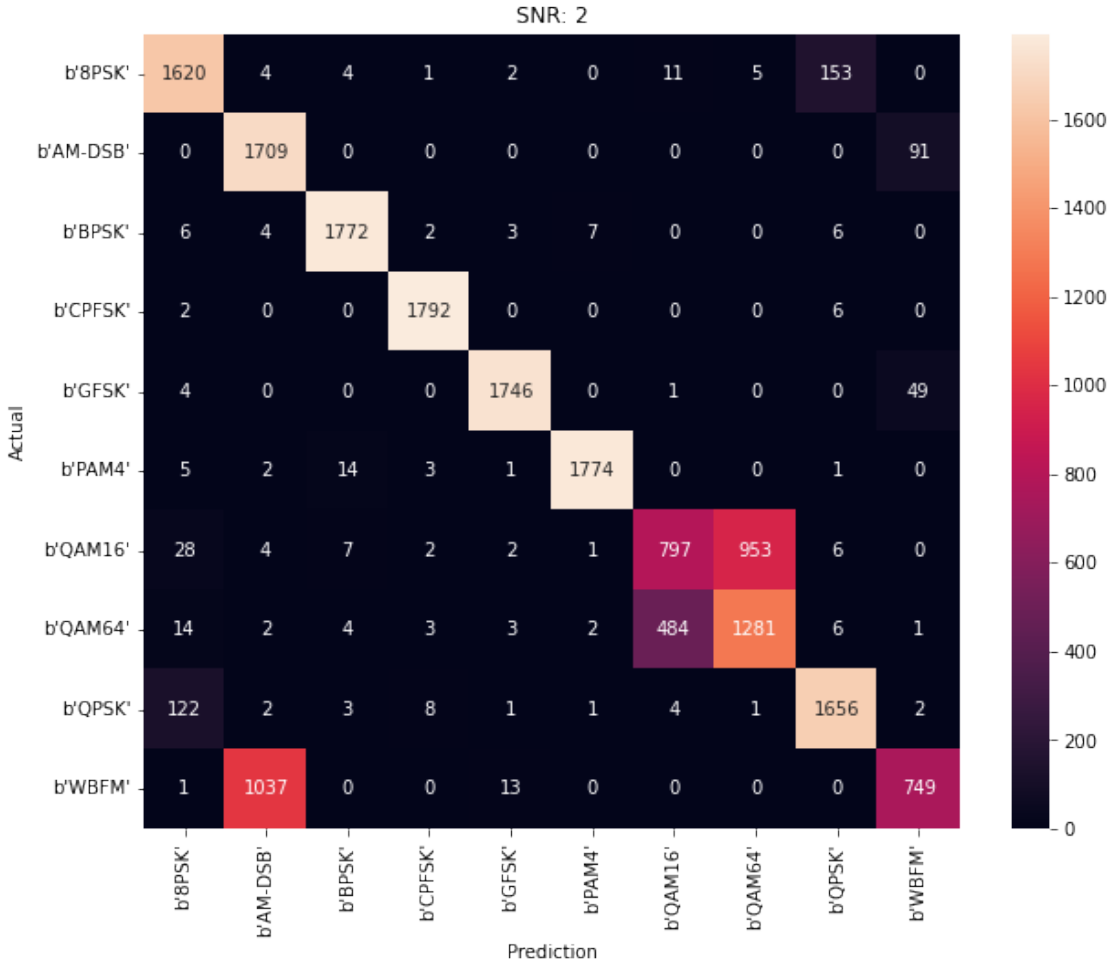

```
Accuracy at SNR = -2 is 0.7220555555555556%
```



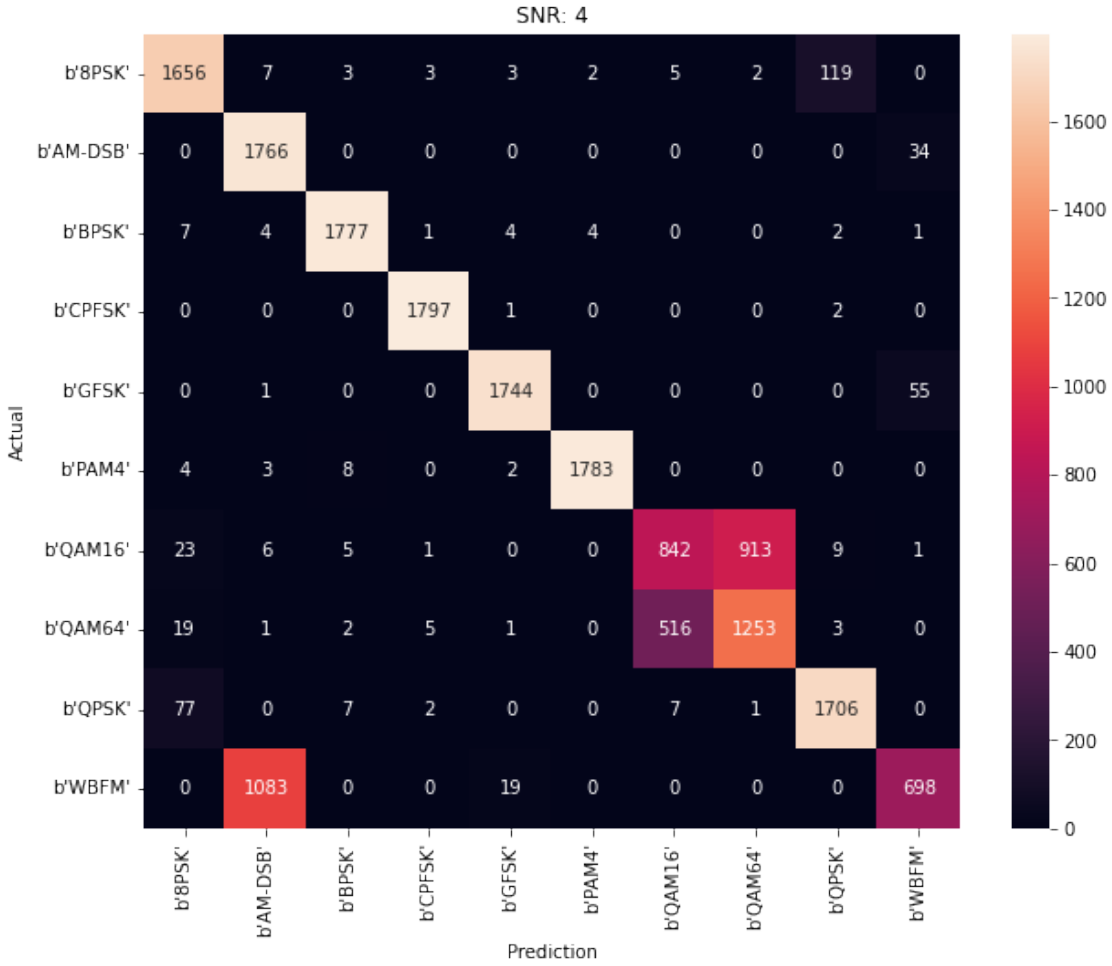

```
Accuracy at SNR = 0 is 0.7967777777777778%
```



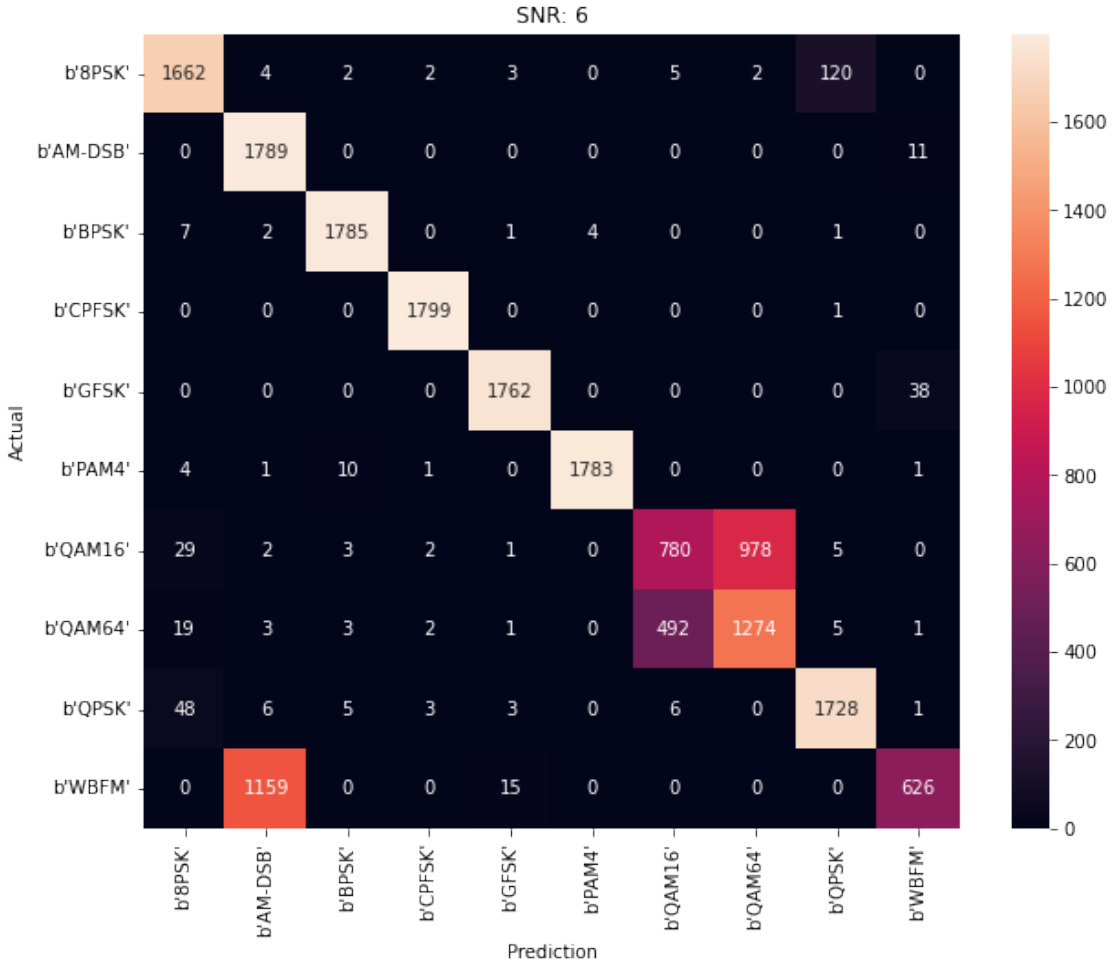

```
Accuracy at SNR = 2 is 0.8275555555555556%
```



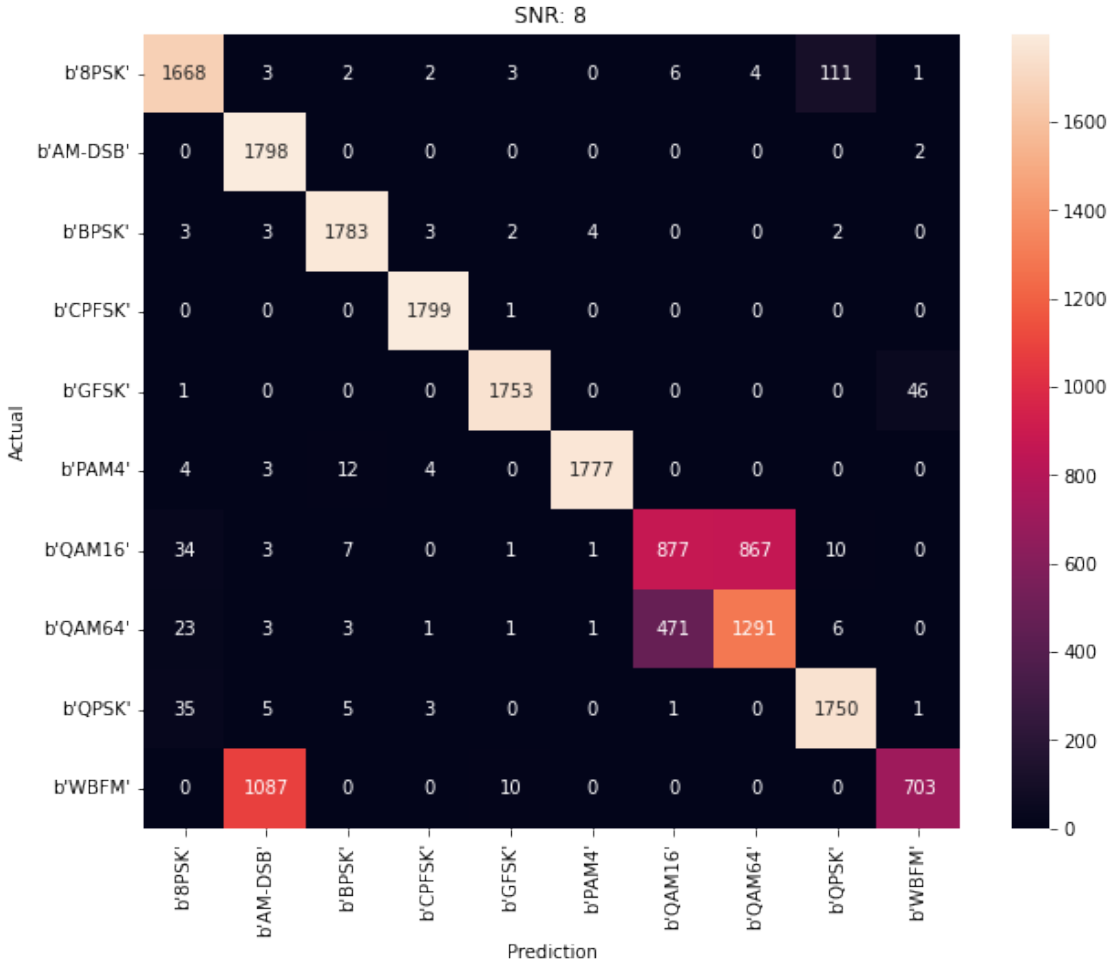

```
Accuracy at SNR = 4 is 0.8345555555555556%
```



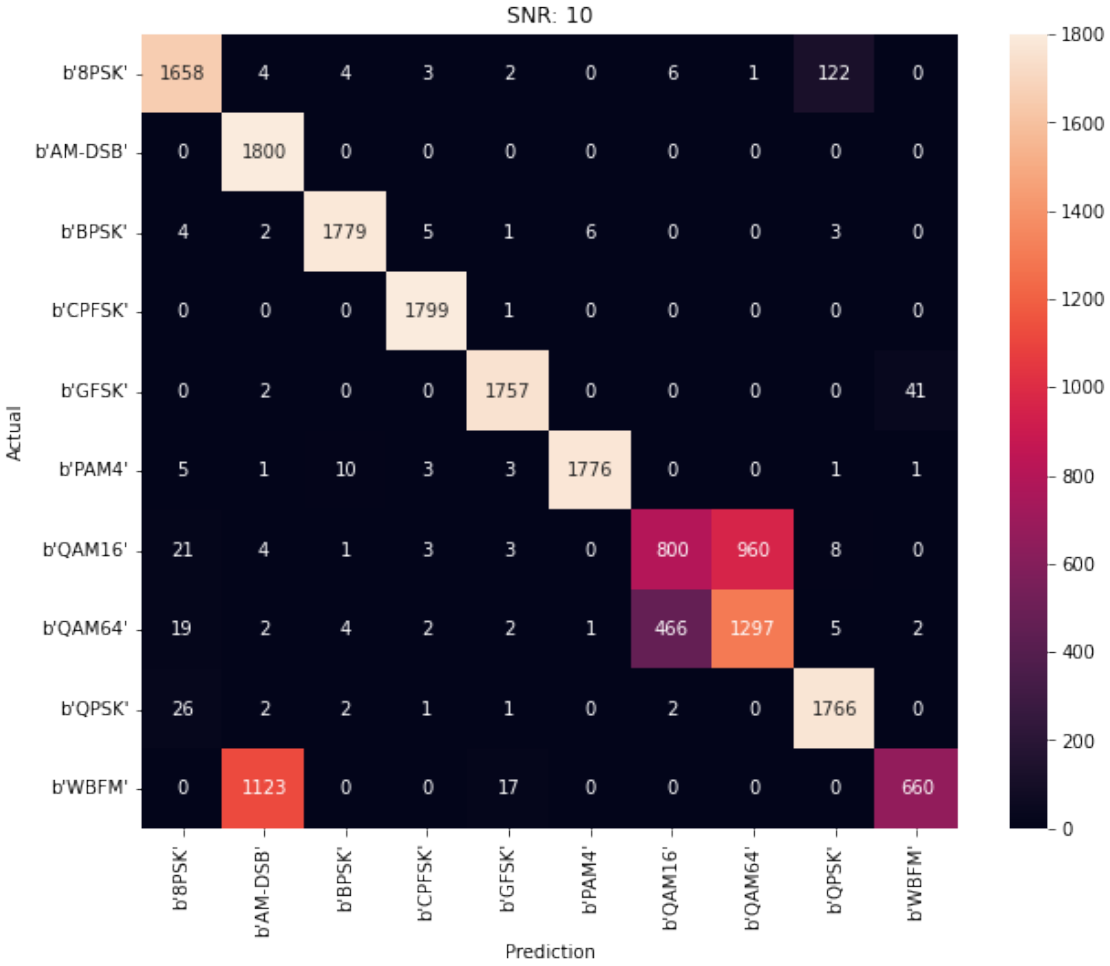
Accuracy at SNR = 6 is 0.8326666666666667%



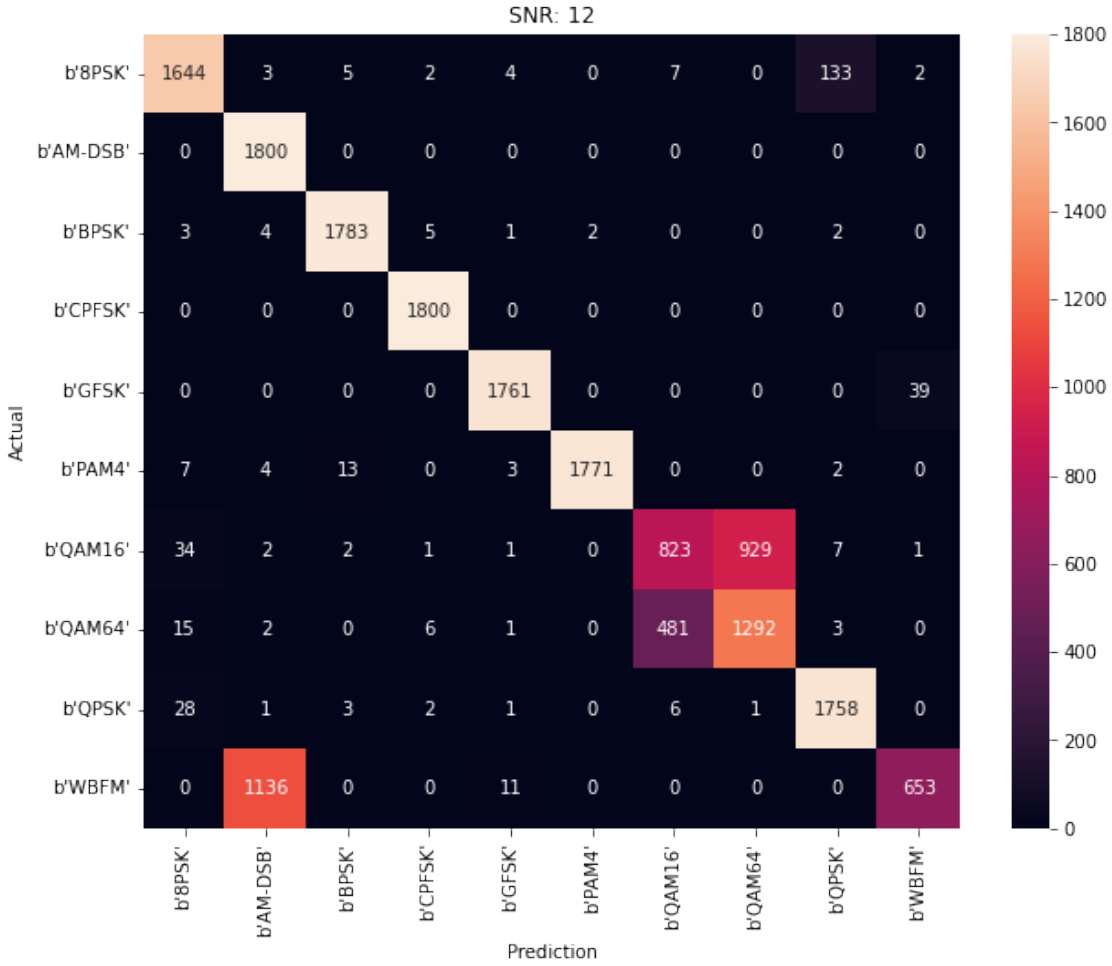

```
Accuracy at SNR = 8 is 0.8443888888888889%
```



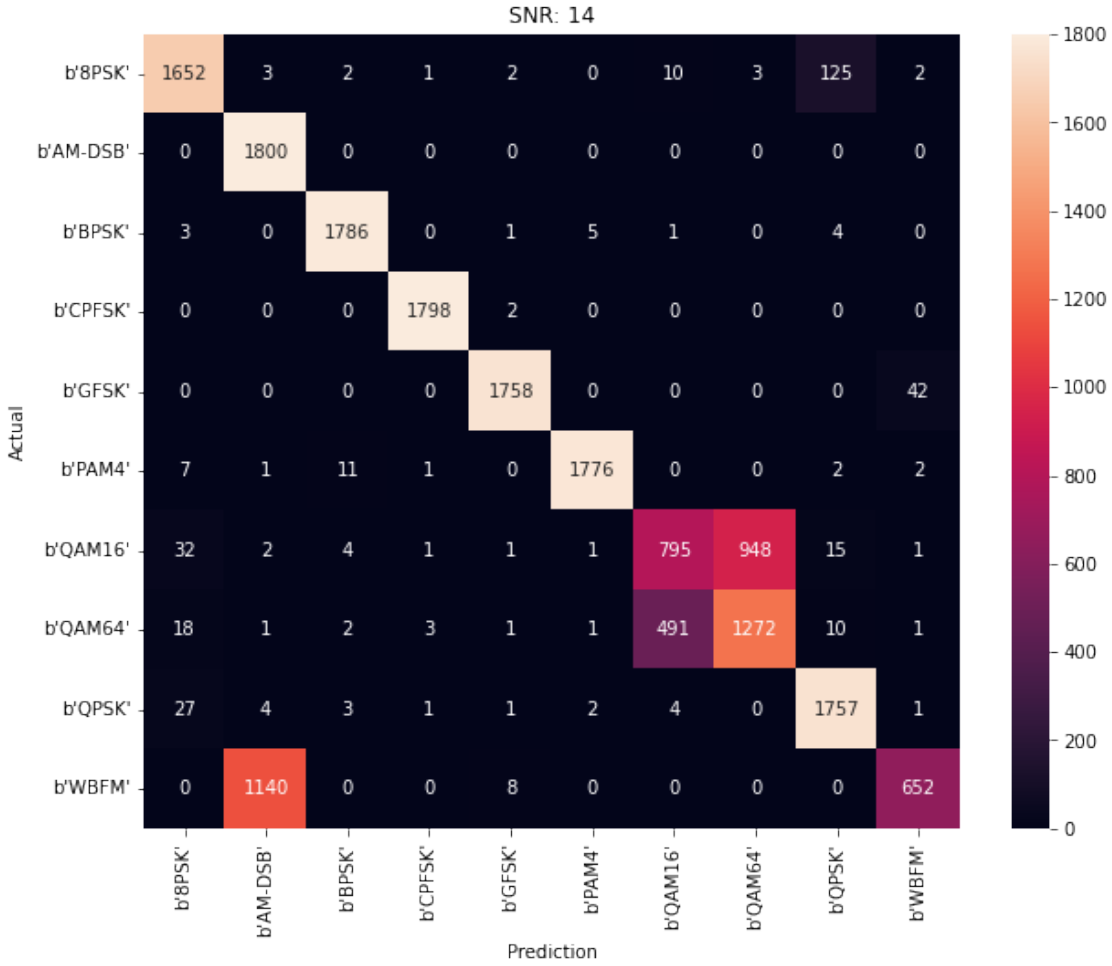

```
Accuracy at SNR = 10 is 0.8384444444444444%
```



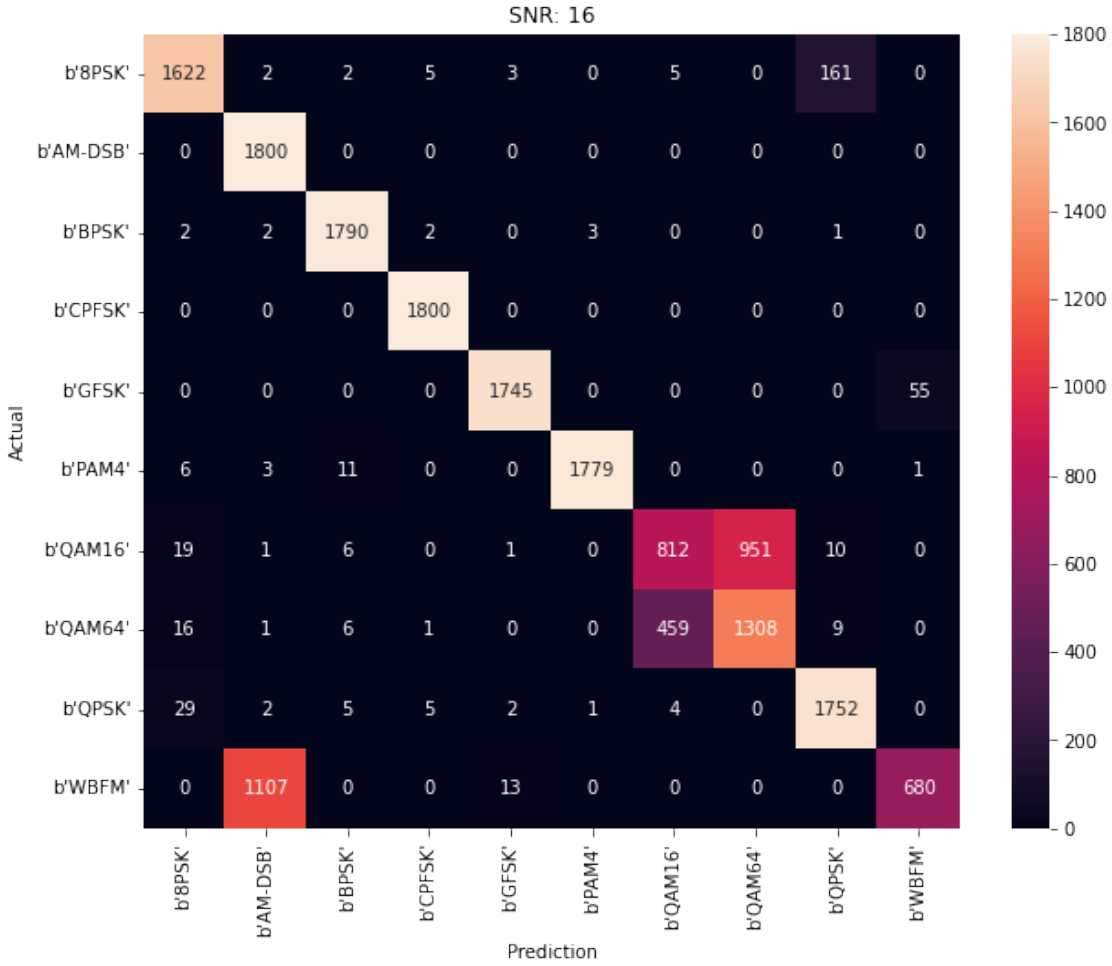
Accuracy at SNR = 12 is 0.8380555555555556%



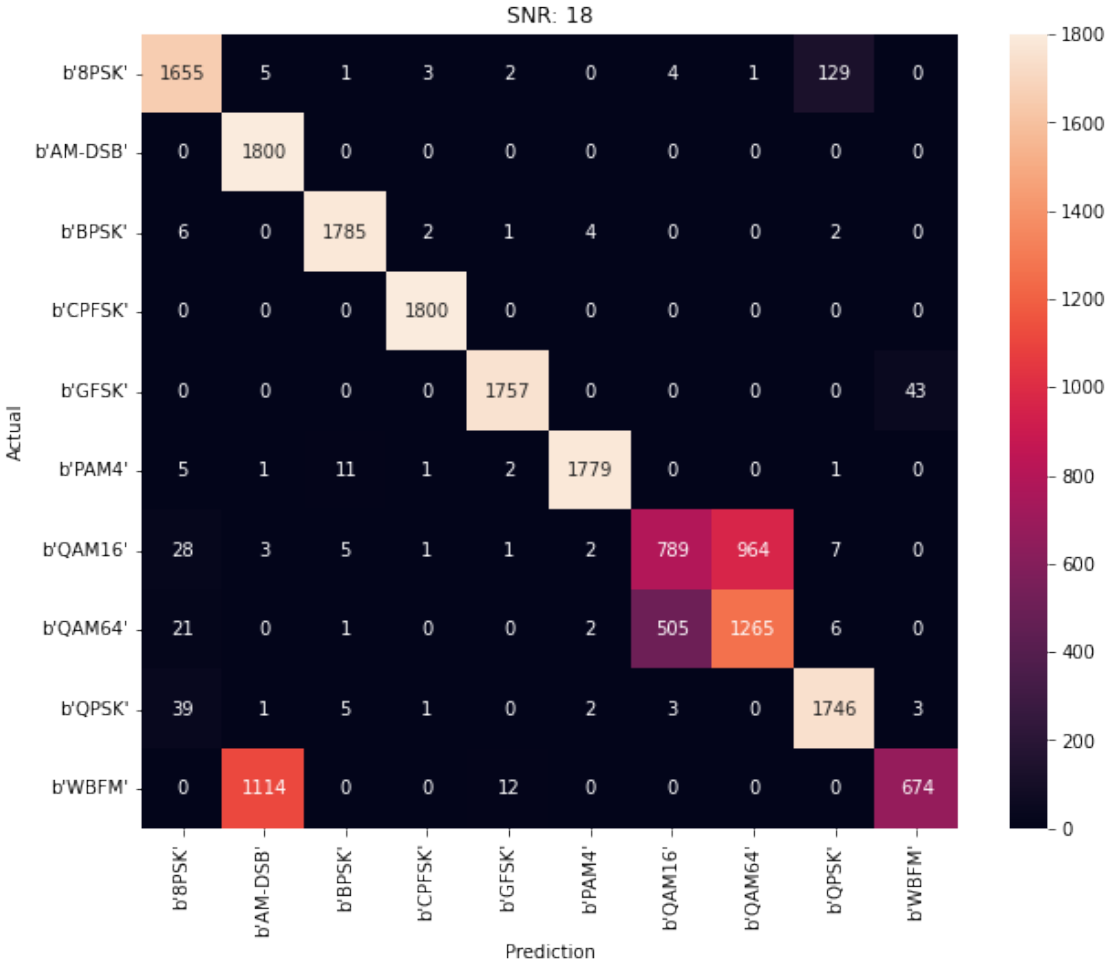

```
Accuracy at SNR = 14 is 0.8358888888888889%
```

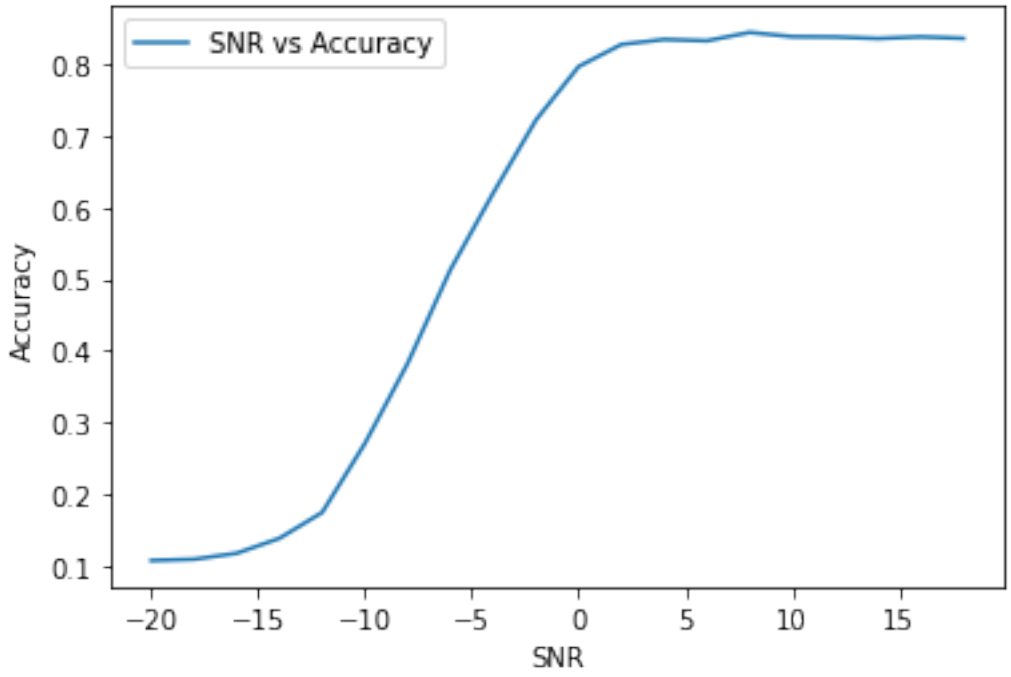



```
Accuracy at SNR = 16 is 0.8382222222222222%
```



Accuracy at SNR = 18 is 0.8361111111111111%


SNR: 18
b'8PSK' 1655 5 1 3 2 0 4 1 129 0
b'AM-DSB' 0 1800 0 0 0 0 0 0 0 0
b'BPSK' 6 0 1785 2 1 4 0 0 2 0
b'CPFSK' 0 0 0 1800 0 0 0 0 0 0
b'GFSK' 0 0 0 0 1757 0 0 0 0 43
b'PAM4' 5 1 11 1 2 1779 0 0 1 0
b'QAM16' 28 3 5 1 1 2 789 964 7 0
b'QAM64' 21 0 1 0 0 2 505 1265 6 0
b'QPSK' 39 1 5 1 0 2 3 0 1746 3
b'WBFM' 0 1114 0 0 12 0 0 0 0 674
Actual
b'8PSK' b'AM-DSB' b'BPSK' b'CPFSK' b'GFSK' b'PAM4' b'QAM16' b'QAM64' b'QPSK' b'WBFM'
Prediction
1800 1600 1400 1200 1000 800 600 400 200 0



6.2 Reshaping data for RNN and LSTM models

[ ]:
```
training_data, validation_data, testing_data =␣
↪reshape_data_for_rnn_lstm(training_data, validation_data, testing_data)
```

[ ]:
```
print('training data shape:', training_data.shape)
print('validation data shape:', validation_data.shape)
print('testing data shape:', testing_data.shape)
```

```
training data shape: (798000, 2, 128)
validation data shape: (42000, 2, 128)
testing data shape: (360000, 2, 128)
```

6.3 RNN Model

[ ]:
```
learning_rate = 0.001
batch_size = 512
epochs = 200
```

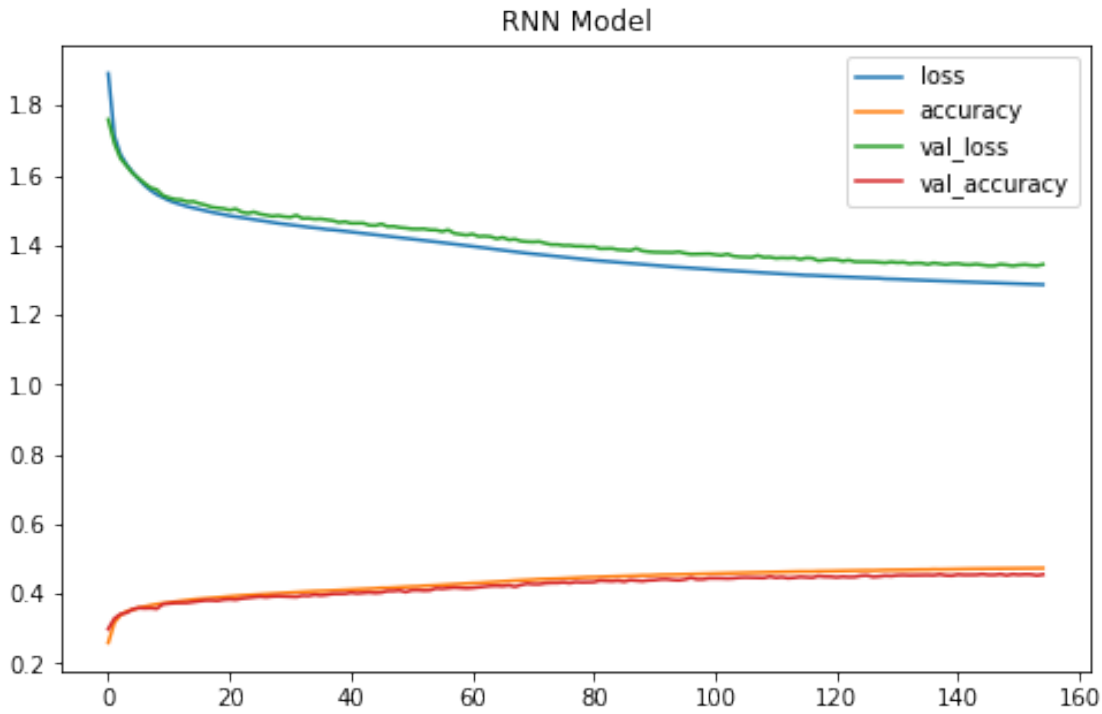
[ ]:
```
rnn_model = Sequential()
rnn_model.add(SimpleRNN(128, activation='relu'))
#rnn_model.add(Dropout(0.5))
rnn_model.add(Dense(10, activation='softmax'))
```

```
rnn_model.compile(loss=tf.keras.losses.CategoricalCrossentropy(),␣
 ↪metrics='accuracy', optimizer=tf.keras.optimizers.
 ↪Adam(learning_rate=learning_rate))
```

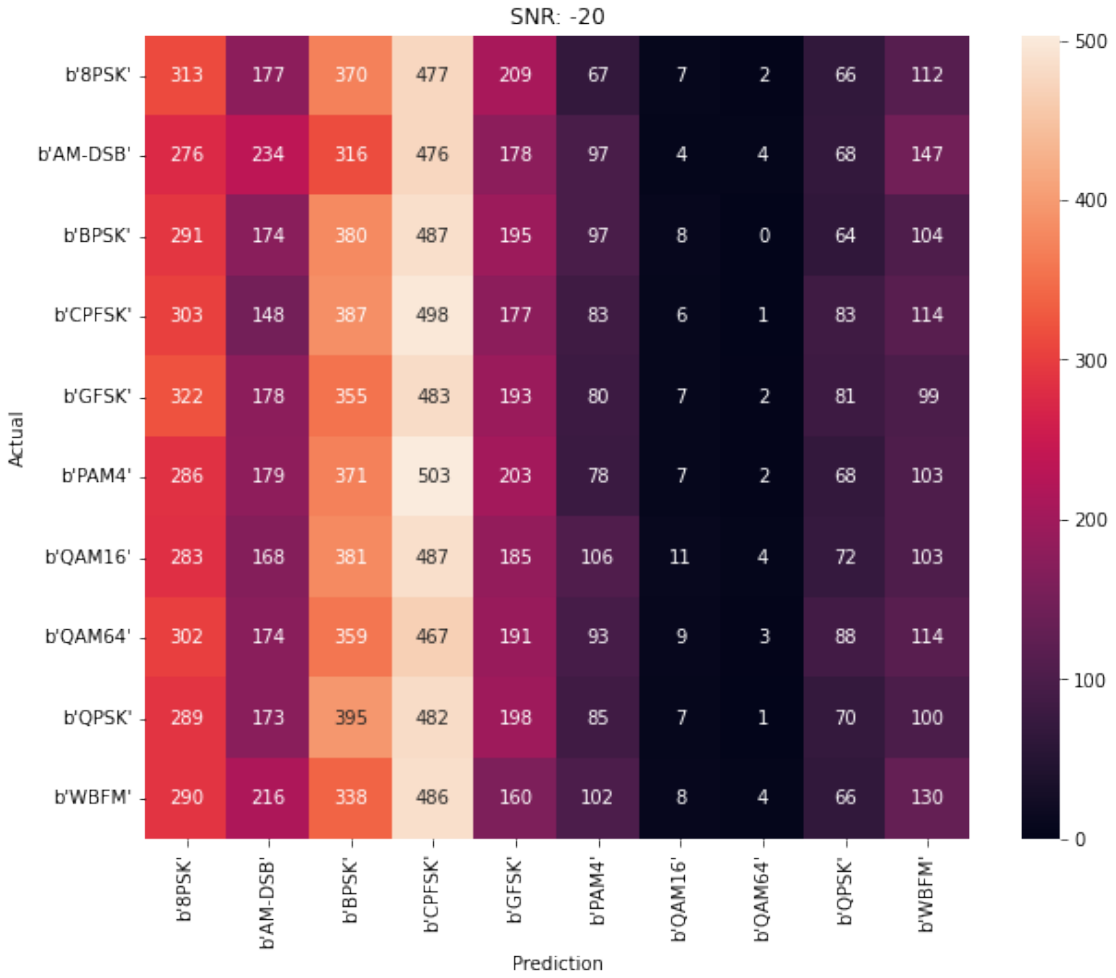
[ ]:
```
es = tf.keras.callbacks.EarlyStopping(monitor="val_loss", patience=5,␣
 ↪restore_best_weights=True,)
checkpointer = ModelCheckpoint(filepath='saved_models/rnn_classification.hdf5',␣
 ↪verbose=1, save_best_only=True)

with tf.device('/device:GPU:0'):
  history = rnn_model.fit(training_data, training_onehot, batch_size=batch_size,␣
 ↪epochs=epochs, validation_data=(validation_data, validation_onehot),␣
 ↪callbacks=[es, checkpointer], verbose=1)
```

```
Epoch 1/200
1551/1559 [============================>.] - ETA: 0s - loss: 1.8926 - accuracy:
0.2596
Epoch 1: val_loss improved from inf to 1.75984, saving model to
saved_models/rnn_classification.hdf5
1559/1559 [==============================] - 9s 5ms/step - loss: 1.8918 -
accuracy: 0.2598 - val_loss: 1.7598 - val_accuracy: 0.2990

Epoch 155: val_loss did not improve from 1.34014
1559/1559 [==============================] - 9s 6ms/step - loss: 1.2865 -
accuracy: 0.4737 - val_loss: 1.3445 - val_accuracy: 0.4554
```

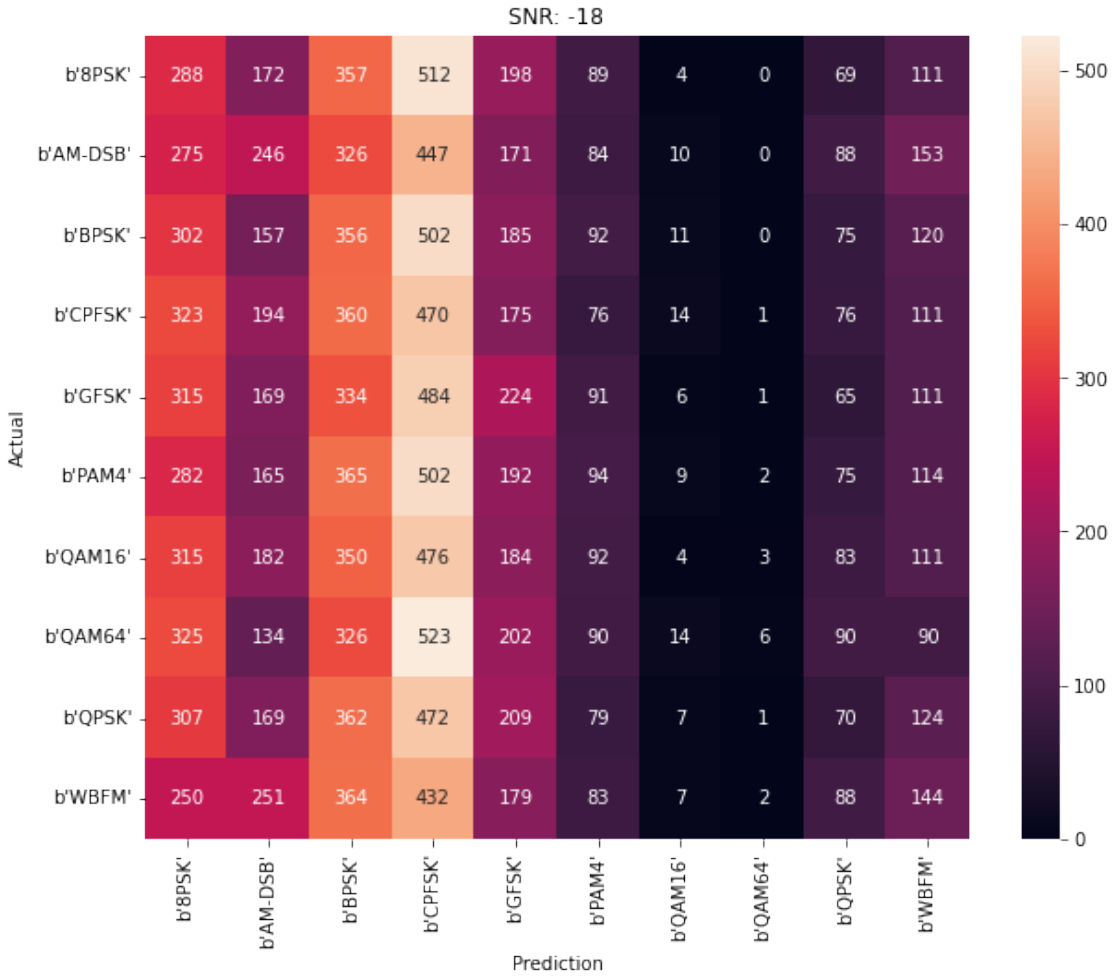
[ ]:
```
plot_model_history(history, 'RNN Model')
model_scoring(rnn_model, history, testing_data, testing_pair_labels)
```



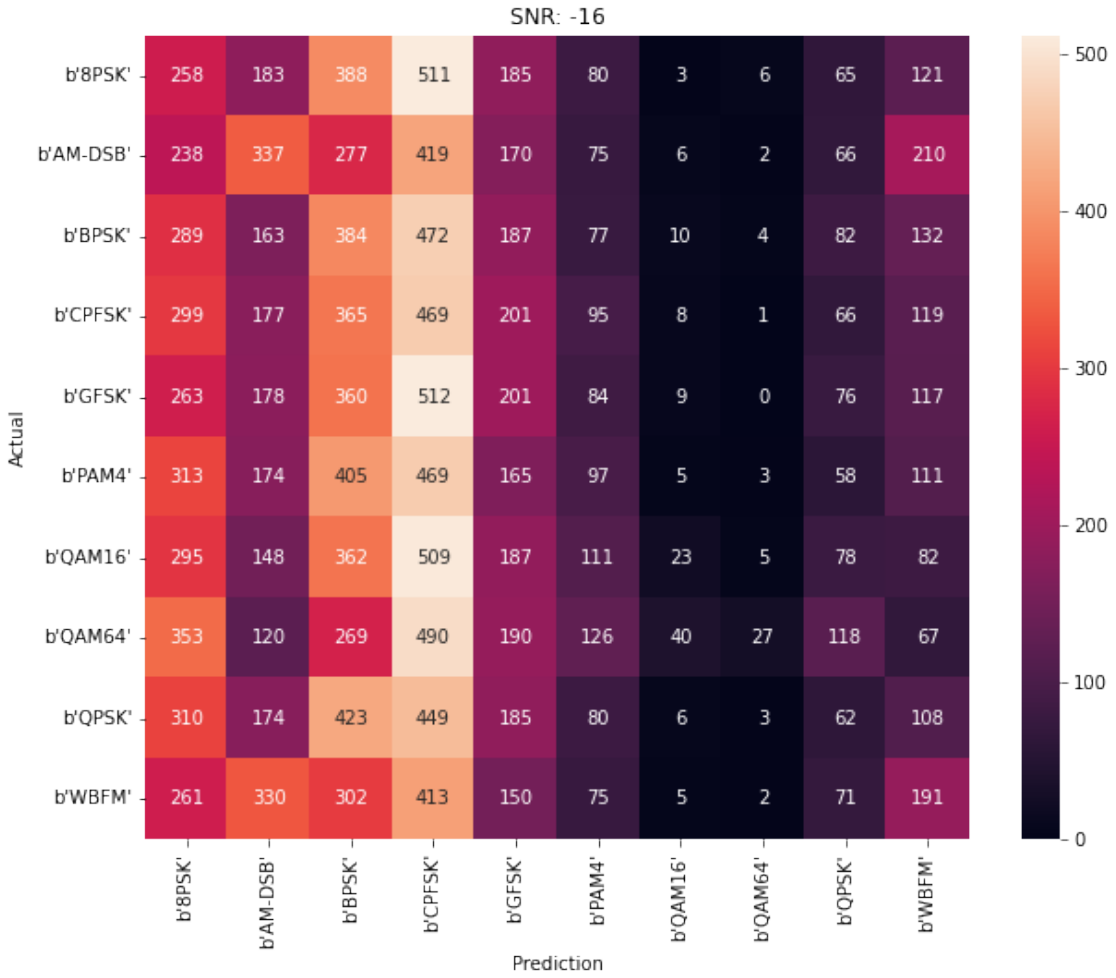

```
Accuracy at SNR = -20 is 0.10611111111111111%
```



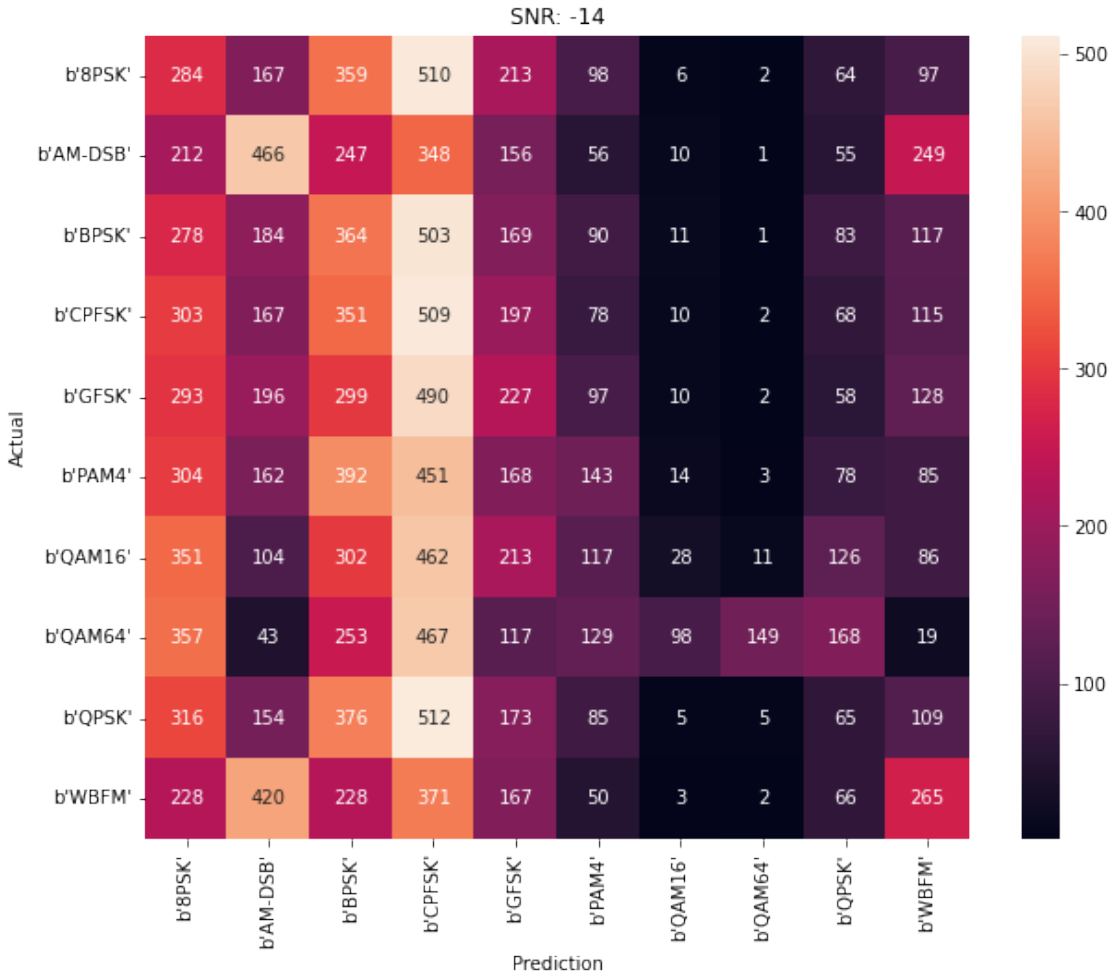
Accuracy at SNR = -18 is 0.10566666666666667%



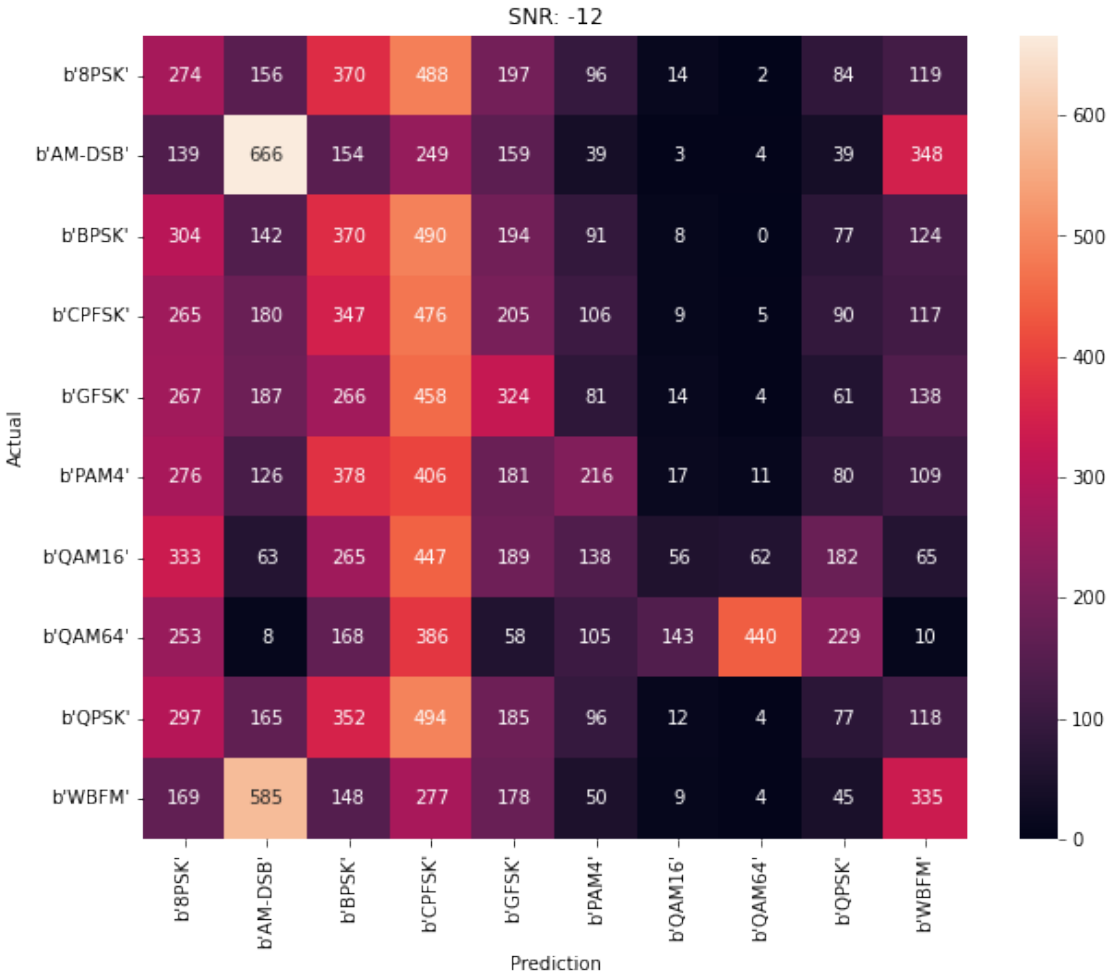

```
Accuracy at SNR = -16 is 0.11383333333333333%
```



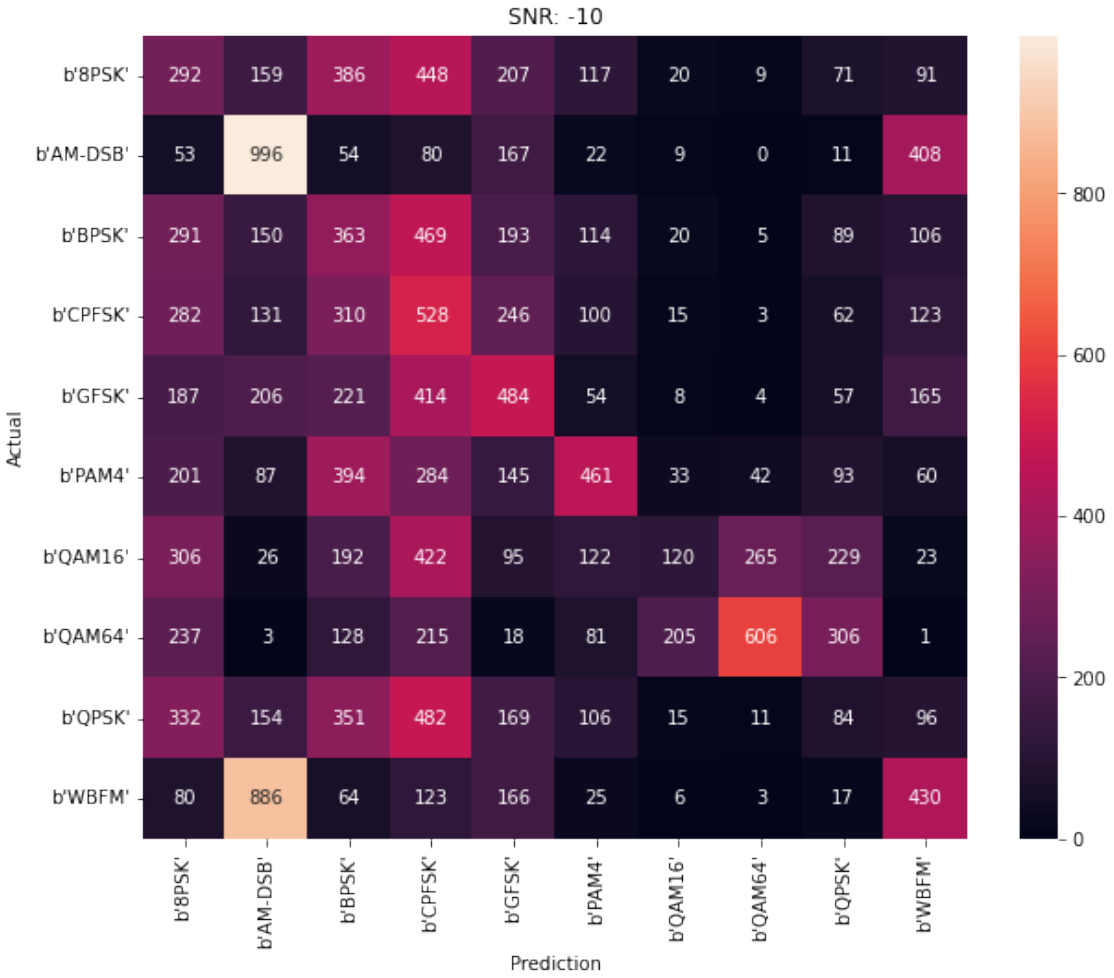
Accuracy at SNR = -14 is 0.1388888888888889%



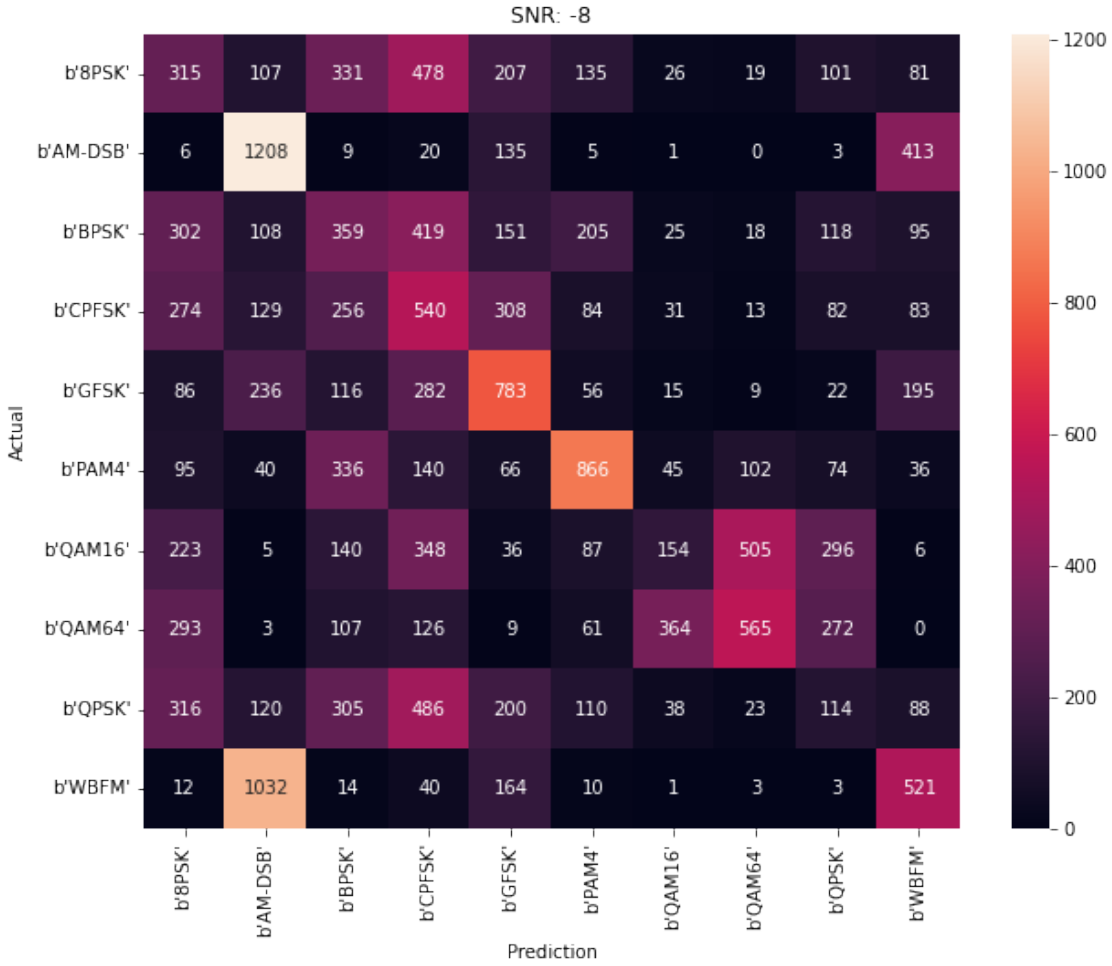

```
Accuracy at SNR = -12 is 0.17966666666666667%
```



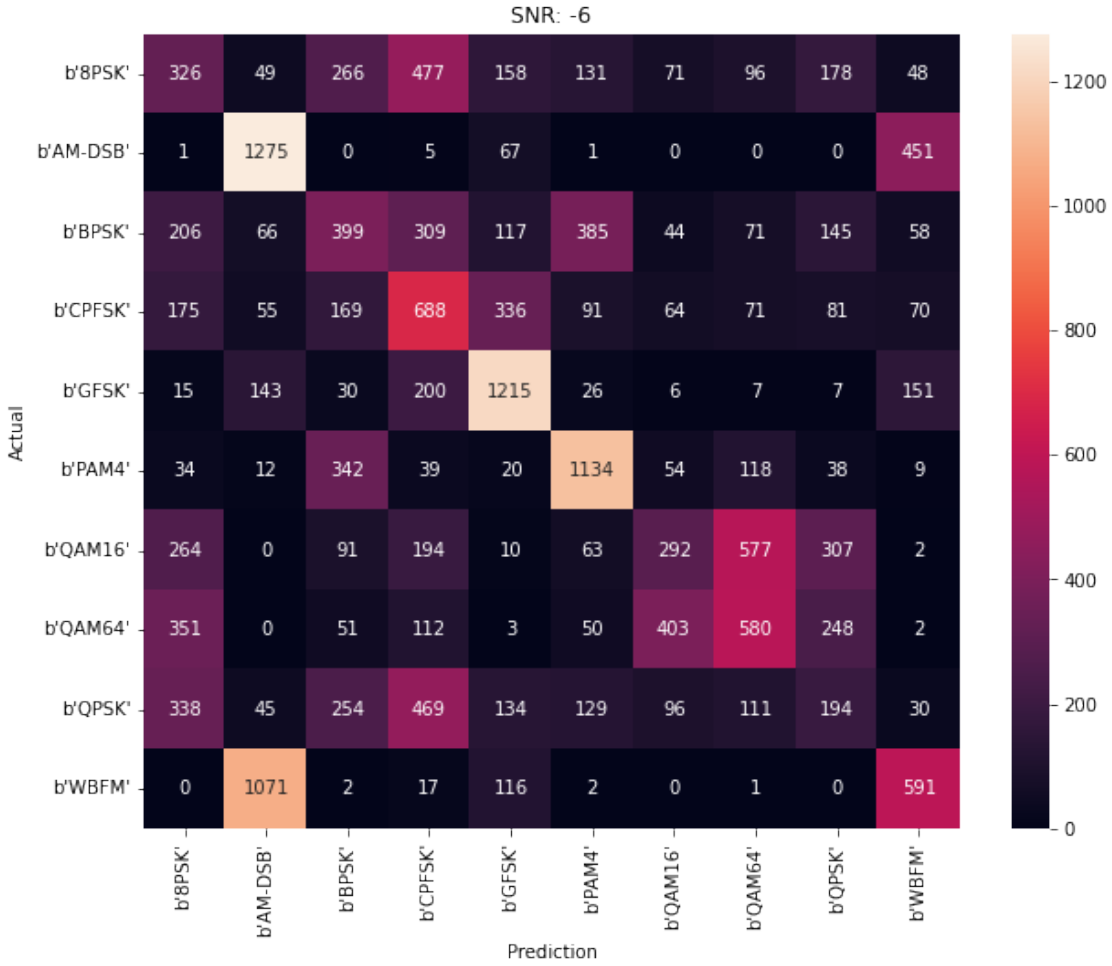
Accuracy at SNR = -10 is 0.24244444444444443%



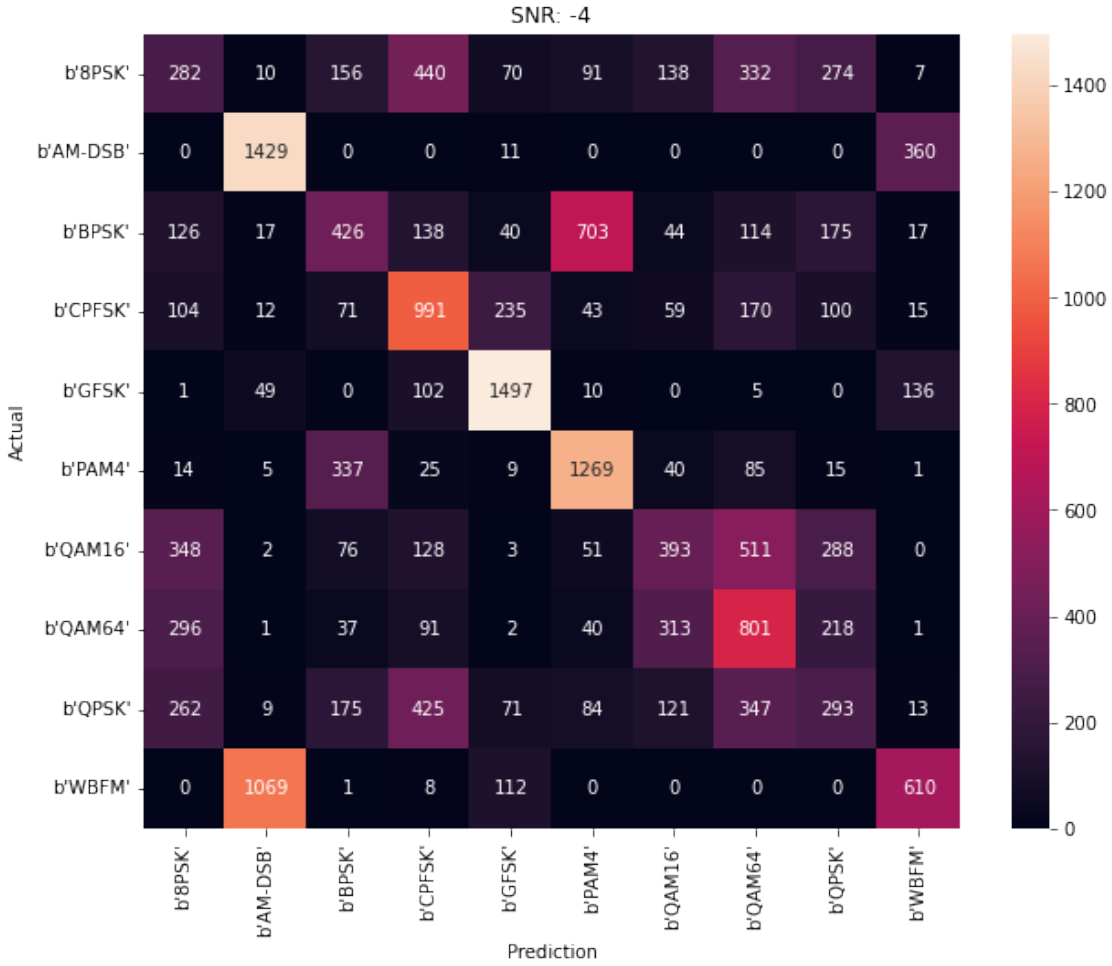

```
Accuracy at SNR = -8 is 0.3013888888888889%
```



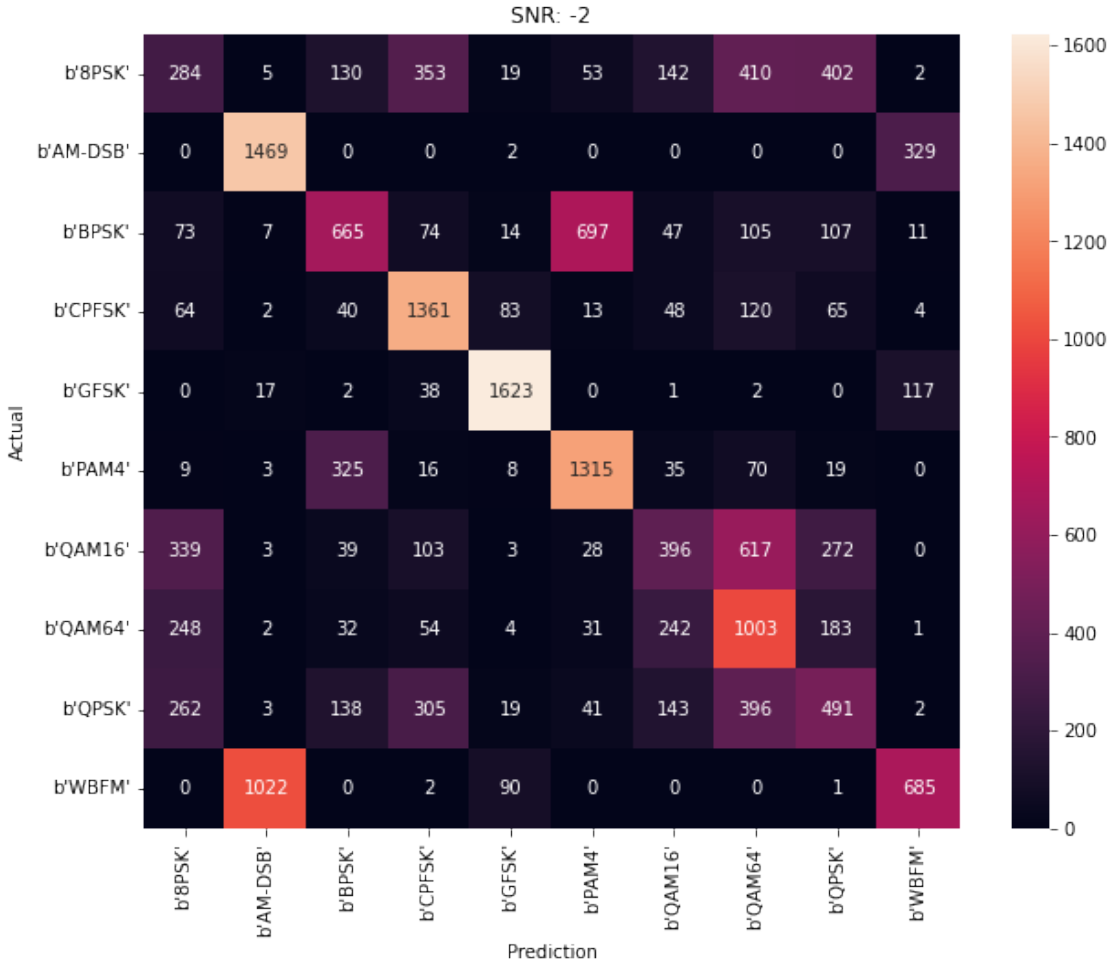
Accuracy at SNR = -6 is 0.3718888888888889%



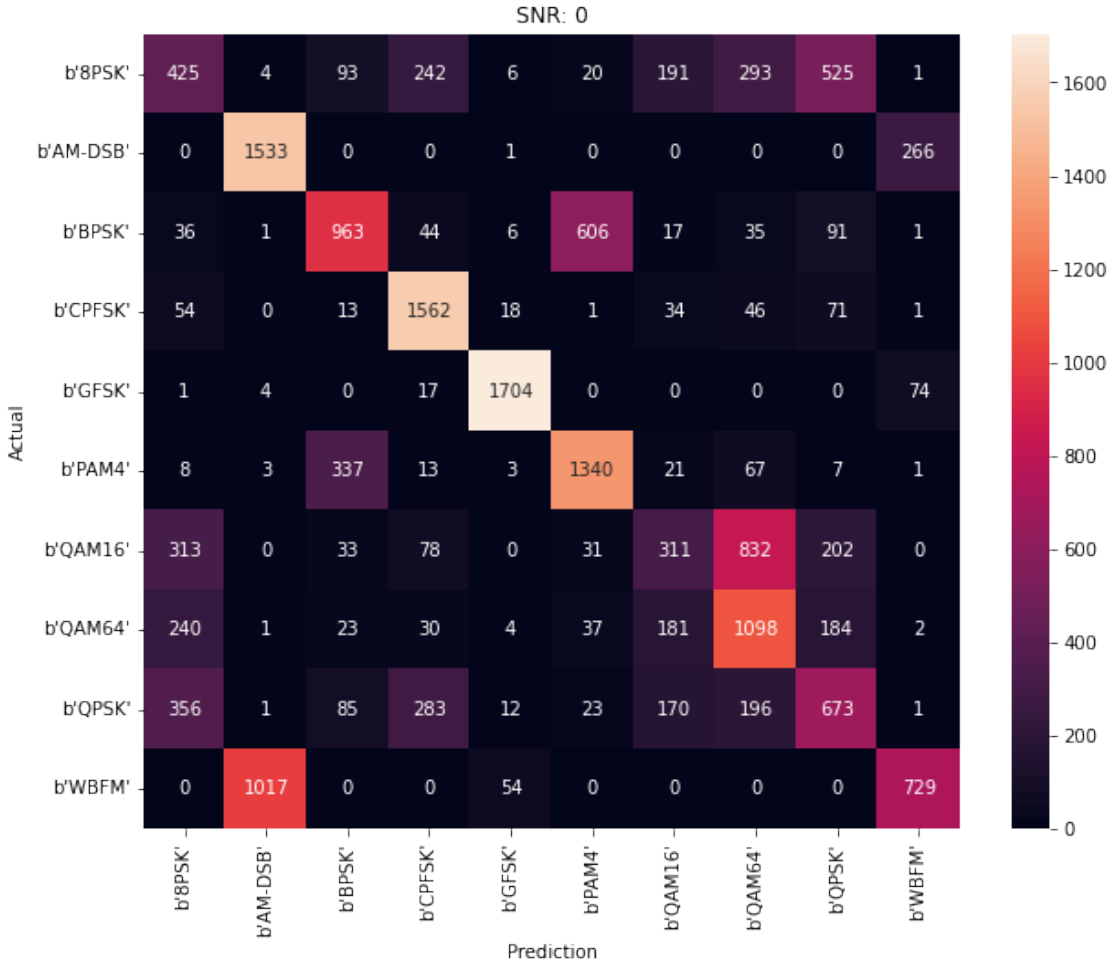

```
Accuracy at SNR = -4 is 0.4439444444444444%
```



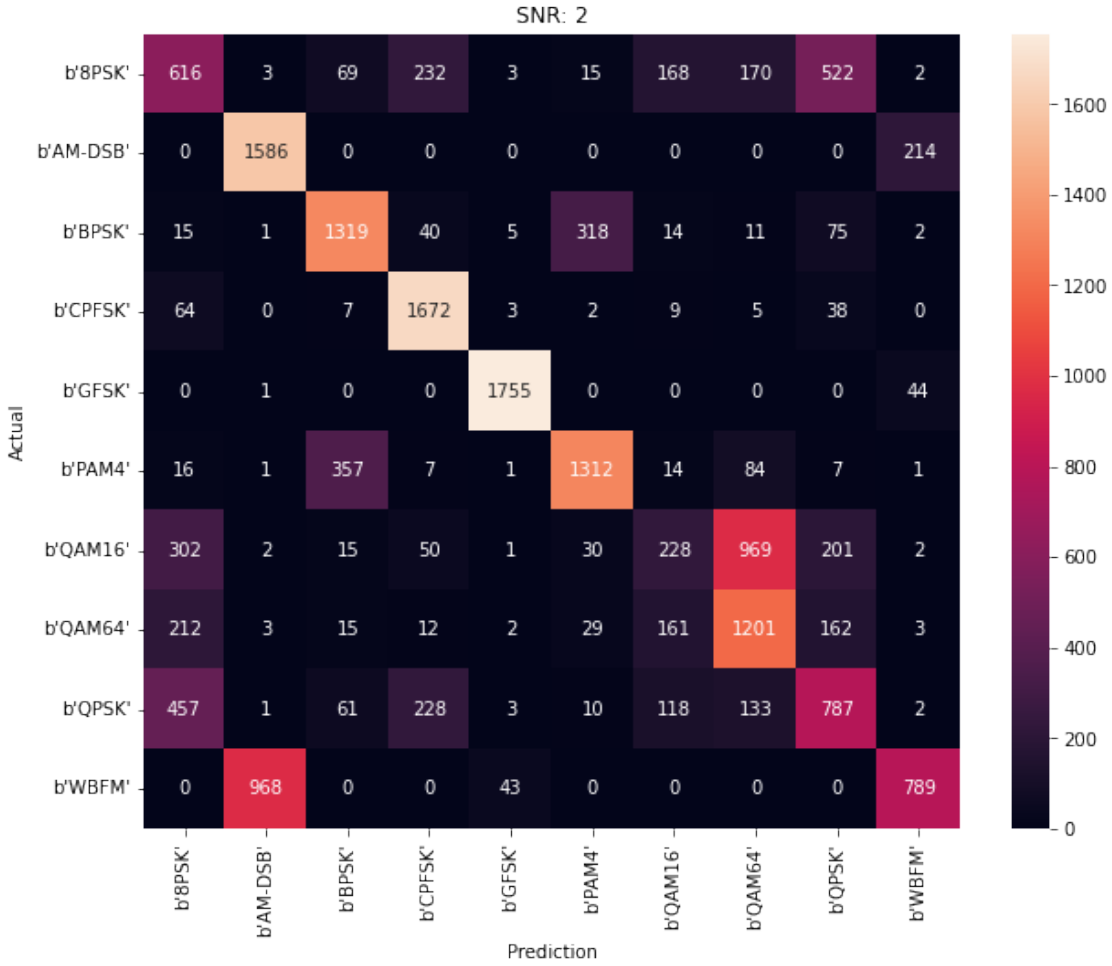

```
Accuracy at SNR = -2 is 0.5162222222222222%
```



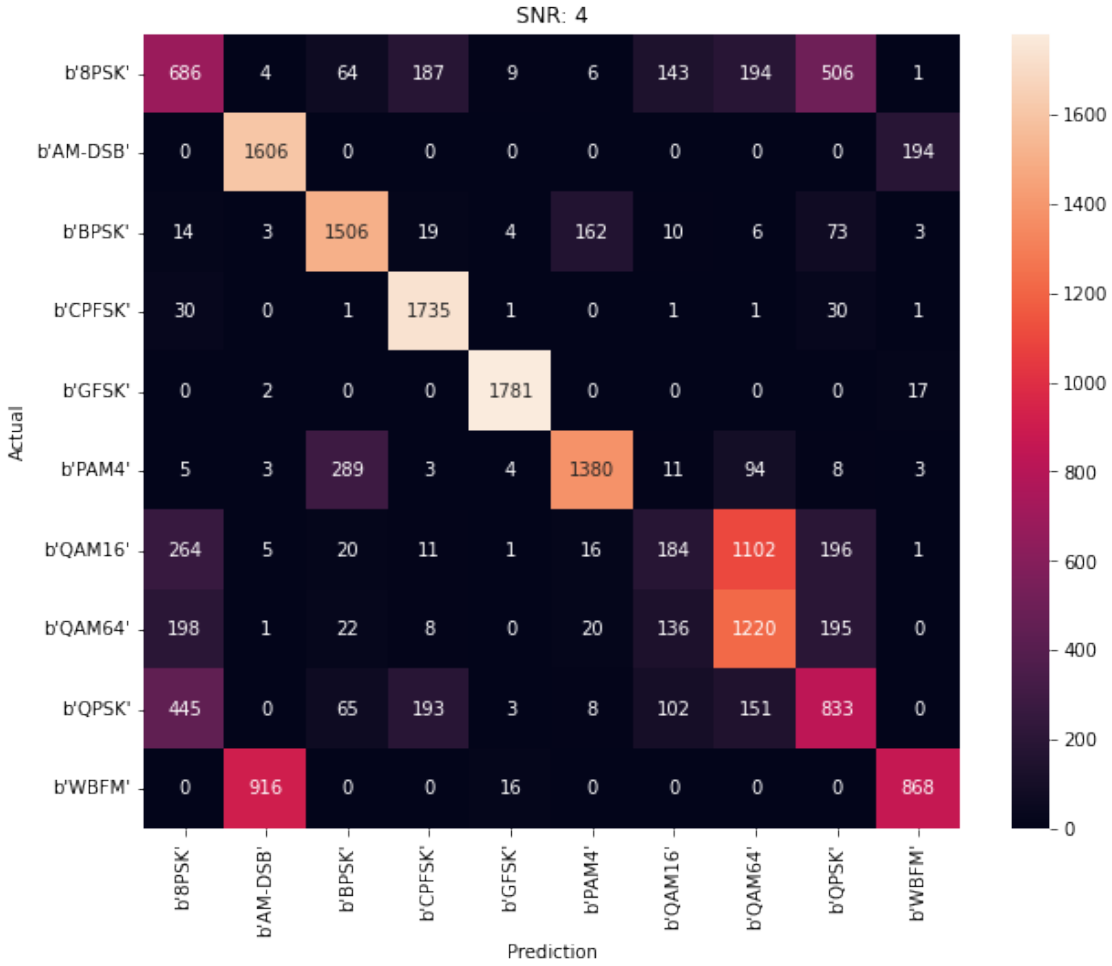
Accuracy at SNR = 0 is 0.5743333333333334%



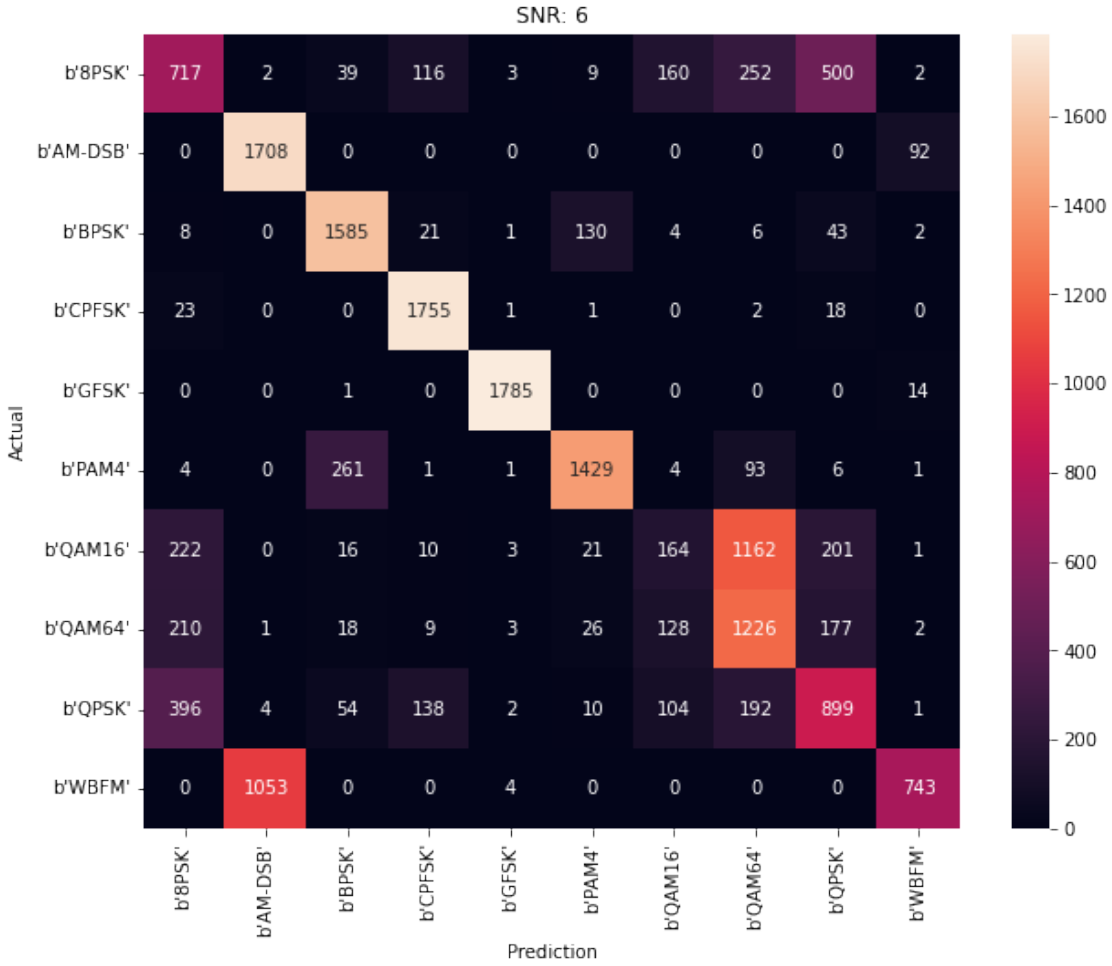
Accuracy at SNR = 2 is 0.6258333333333334%



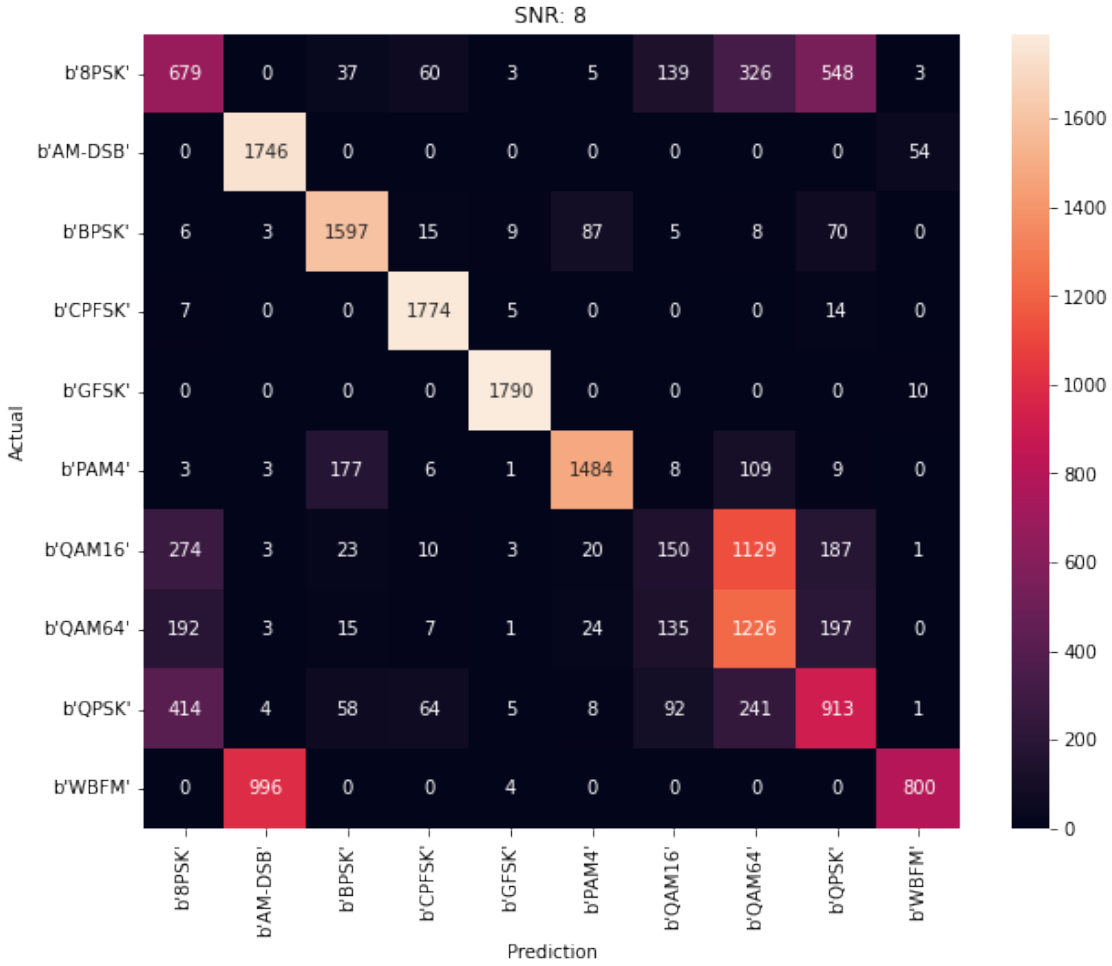
Accuracy at SNR = 4 is 0.6555%



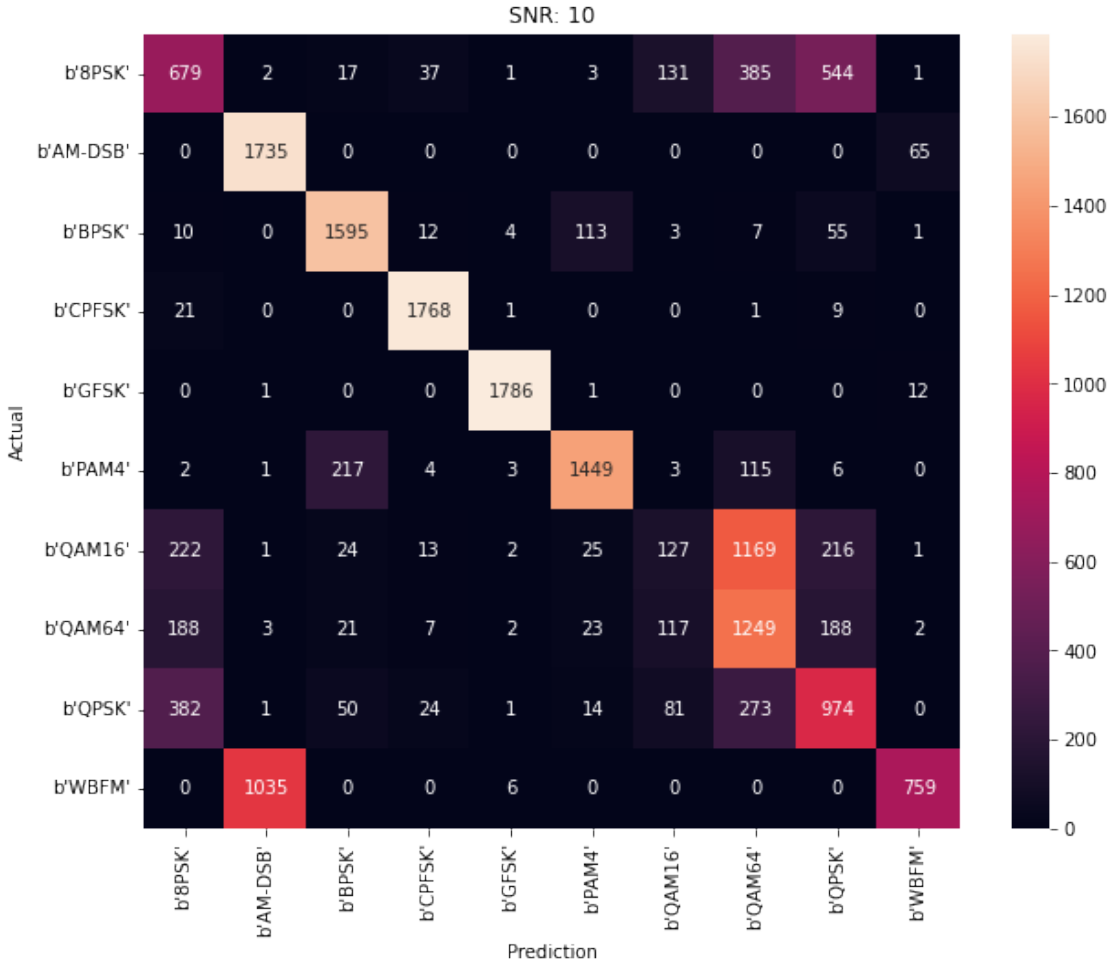
Accuracy at SNR = 6 is 0.6672777777777777%



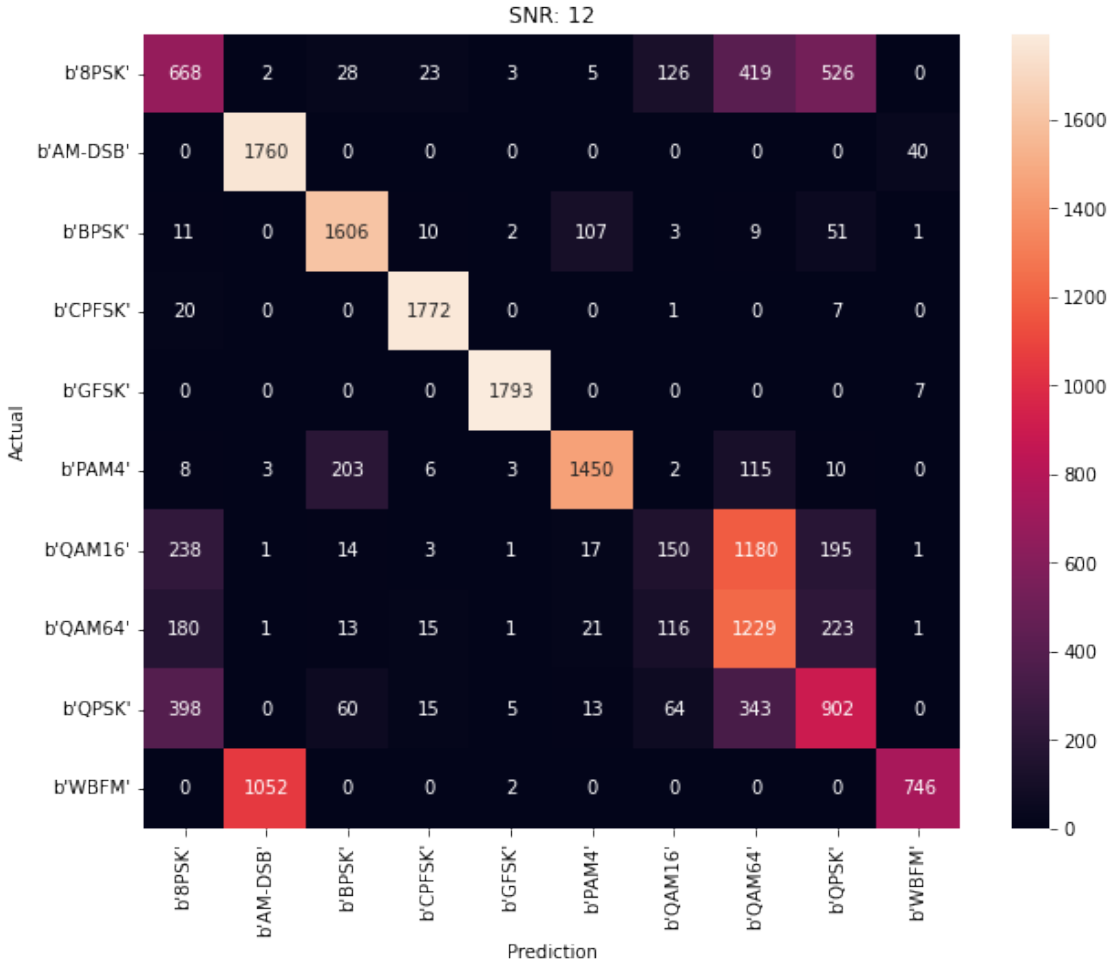

```
Accuracy at SNR = 8 is 0.6755%
```



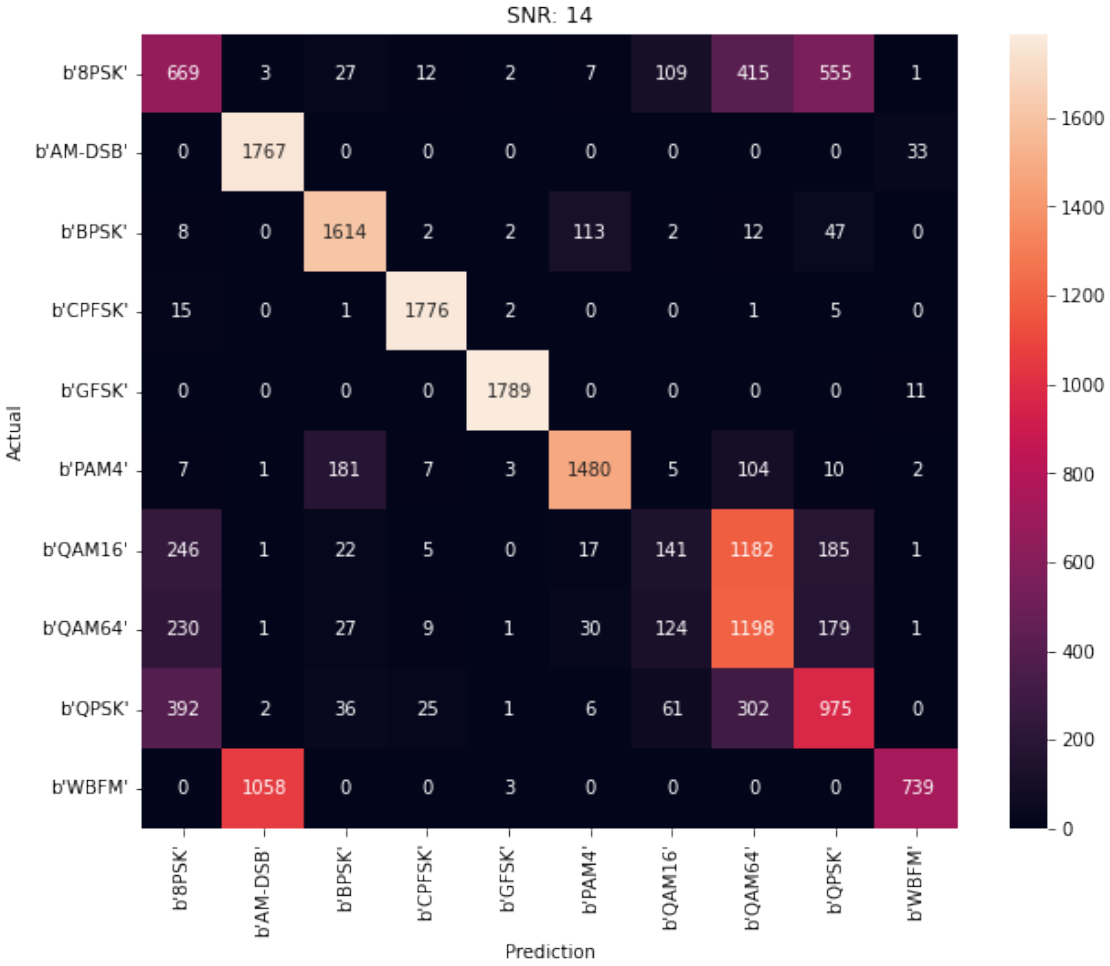

```
Accuracy at SNR = 10 is 0.6733888888888889%
```



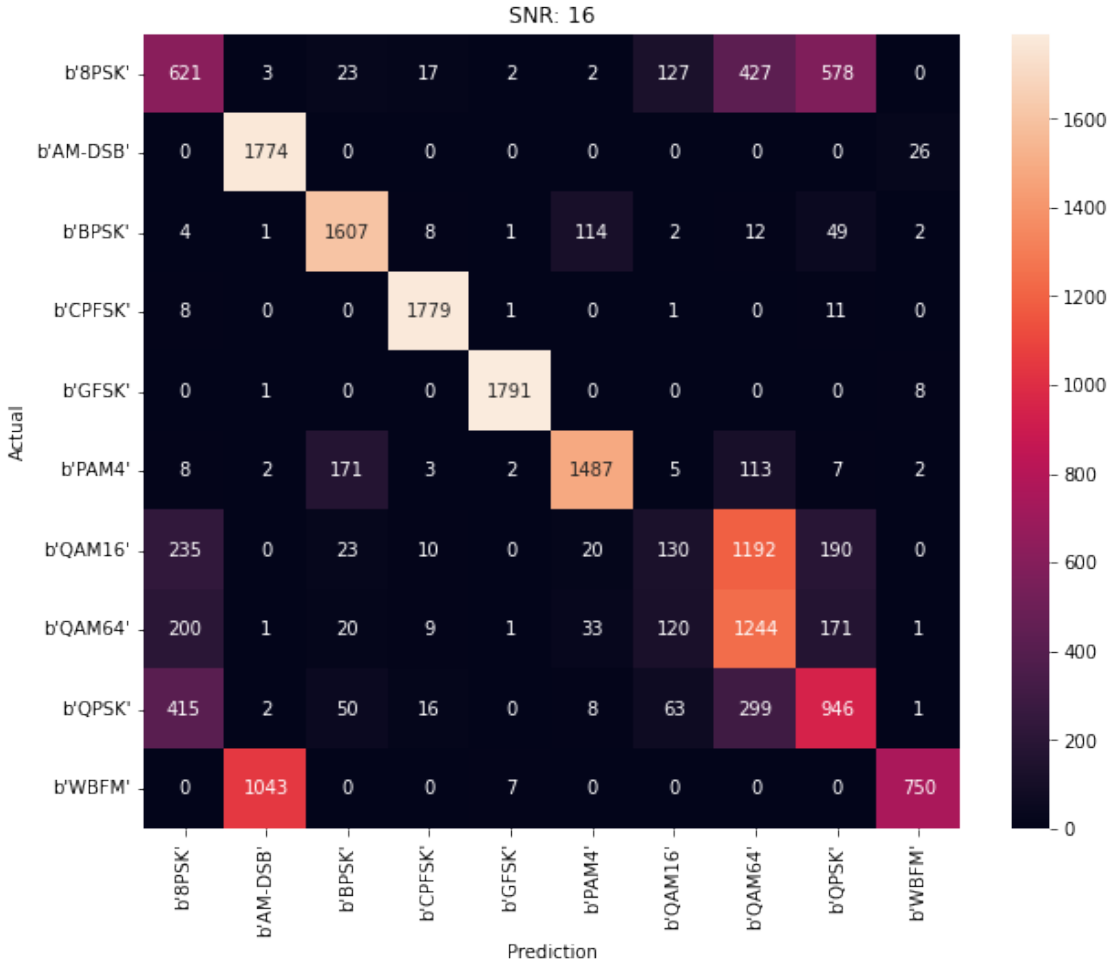
Accuracy at SNR = 12 is 0.6708888888888889%



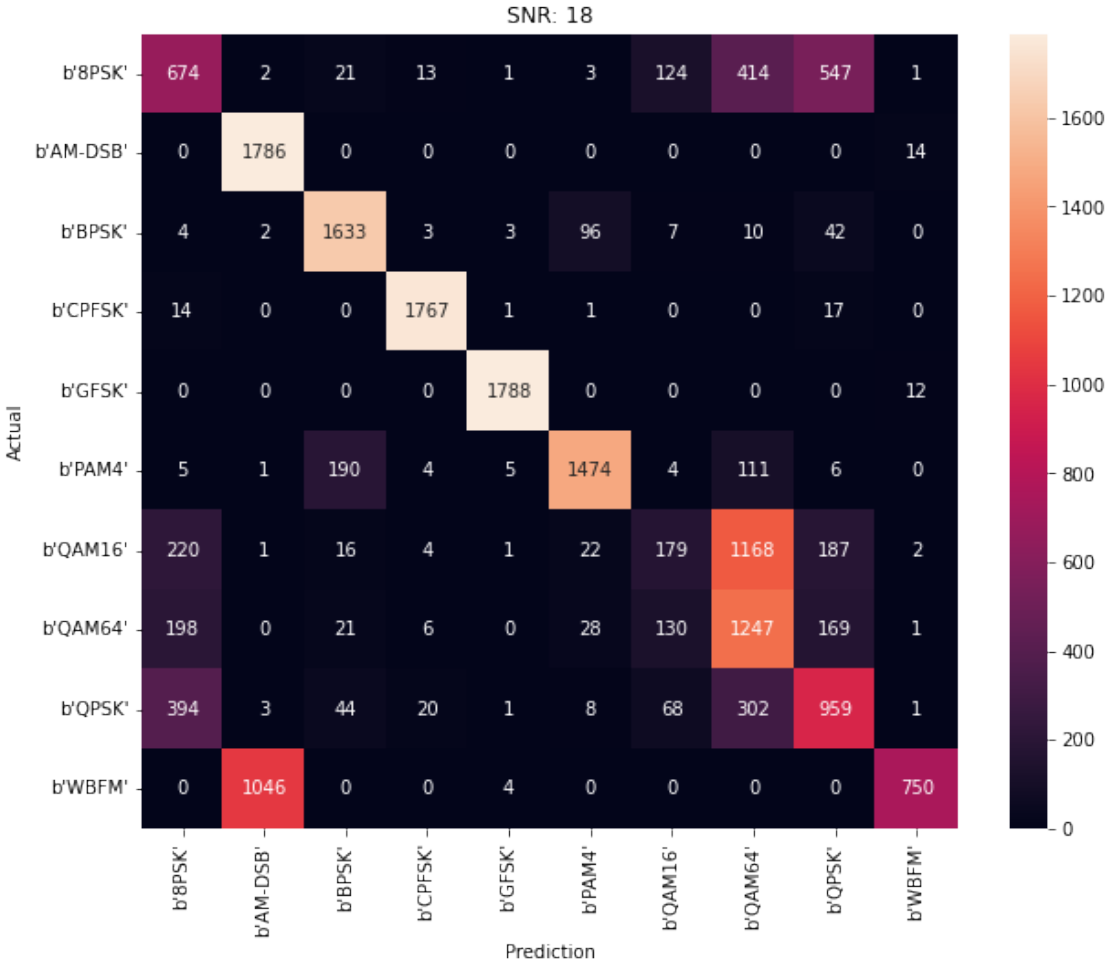

```
Accuracy at SNR = 14 is 0.6748888888888889%
```

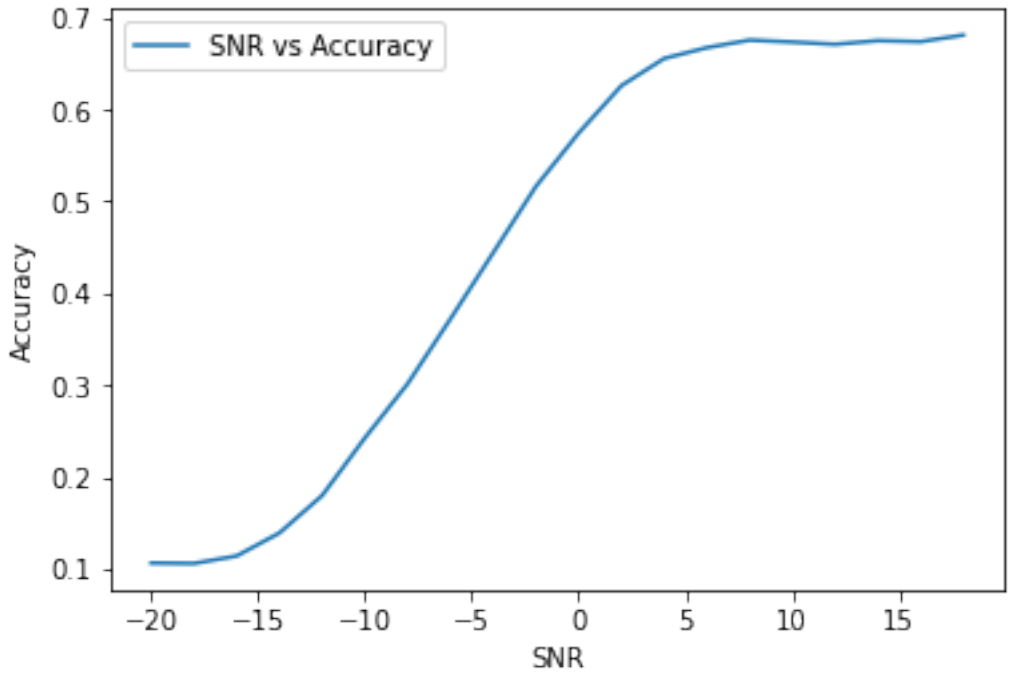



```
Accuracy at SNR = 16 is 0.6738333333333333%
```



Accuracy at SNR = 18 is 0.6809444444444445%


SNR: 18
b'8PSK' 674 2 21 13 1 3 124 414 547 1
b'AM-DSB' 0 1786 0 0 0 0 0 0 0 14
b'BPSK' 4 2 1633 3 3 96 7 10 42 0
b'CPFSK' 14 0 0 1767 1 1 0 0 17 0
b'GFSK' 0 0 0 0 1788 0 0 0 0 12
b'PAM4' 5 1 190 4 5 1474 4 111 6 0
b'QAM16' 220 1 16 4 1 22 179 1168 187 2
b'QAM64' 198 0 21 6 0 28 130 1247 169 1
b'QPSK' 394 3 44 20 1 8 68 302 959 1
b'WBFM' 0 1046 0 0 4 0 0 0 0 750
Actual
b'8PSK' b'AM-DSB' b'BPSK' b'CPFSK' b'GFSK' b'PAM4' b'QAM16' b'QAM64' b'QPSK' b'WBFM'
Prediction
1600 1400 1200 1000 800 600 400 200 0



6.4 LSTM Model

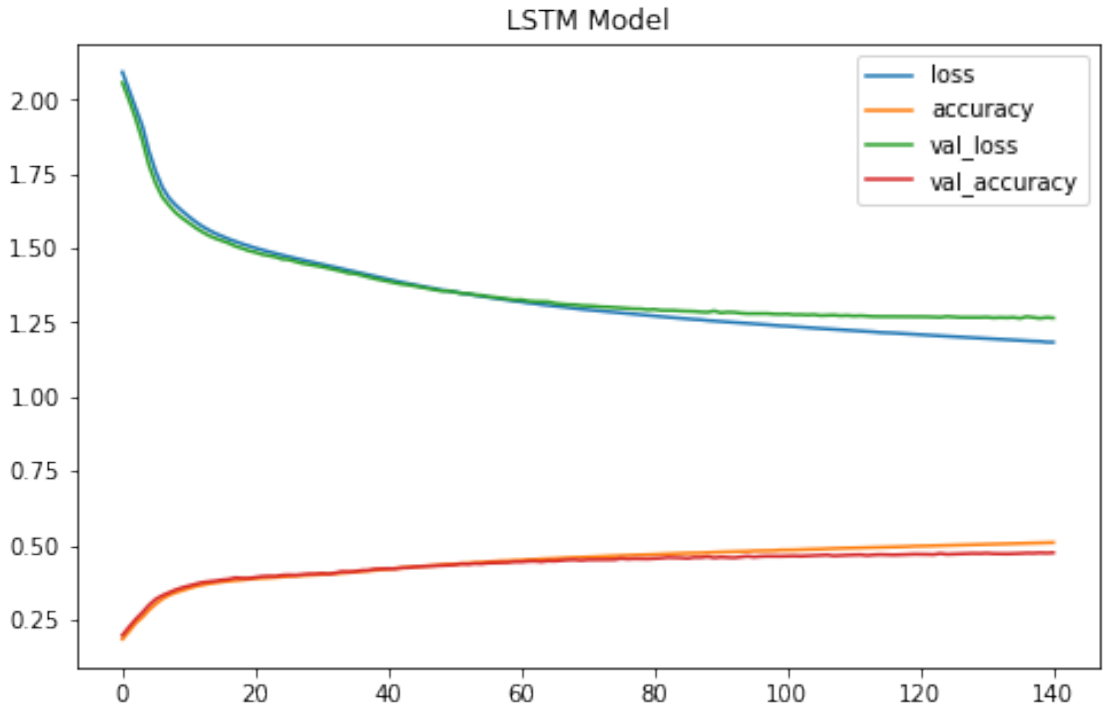
[ ]:
```
learning_rate = 0.001
batch_size = 512
epochs = 200
```

[ ]:
```
lstm_model = Sequential()
lstm_model.add(LSTM(256))
lstm_model.add(Dropout(0.2))
lstm_model.add(Dense(10, activation='softmax'))
lstm_model.compile(loss=tf.keras.losses.CategoricalCrossentropy(),␣
 ↪metrics='accuracy', optimizer=tf.keras.optimizers.
 ↪Adam(learning_rate=learning_rate))
```

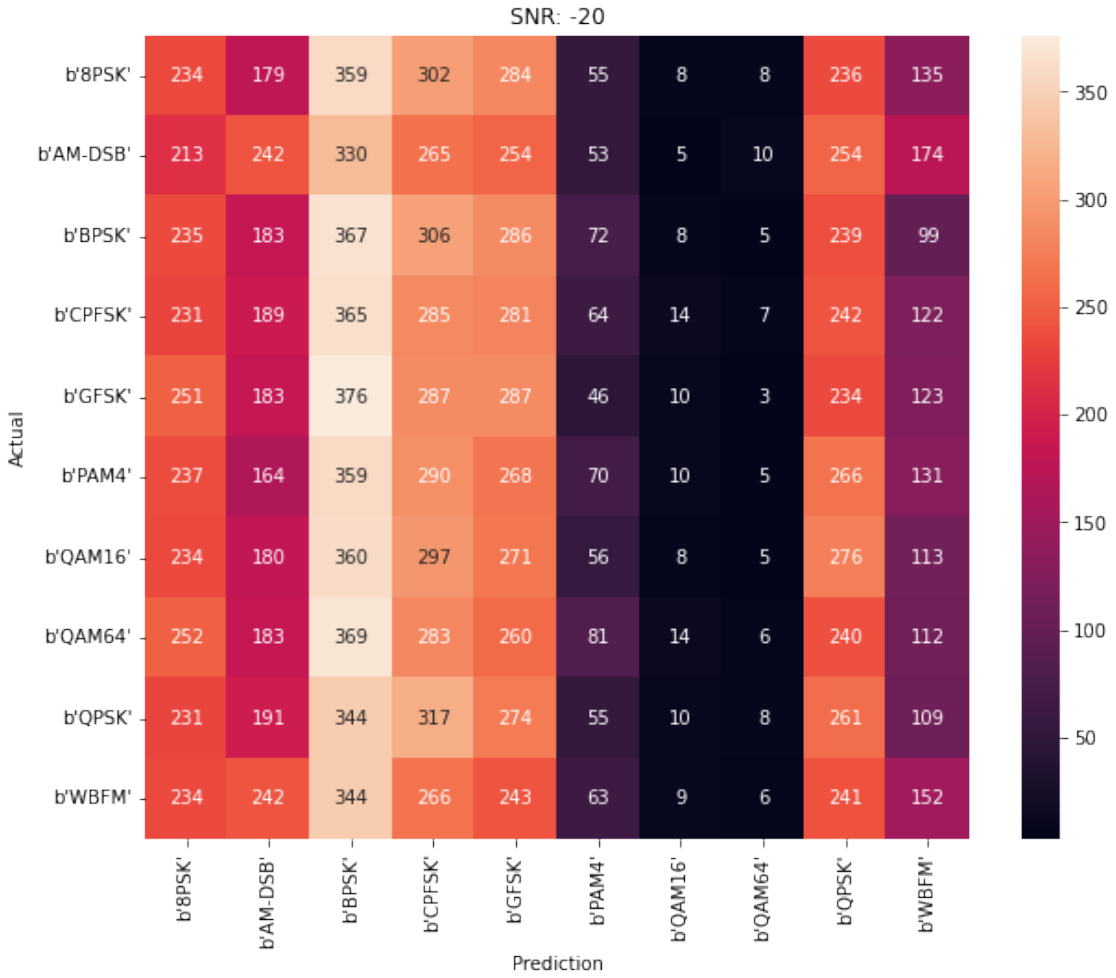
[ ]:
```
es = tf.keras.callbacks.EarlyStopping(monitor="val_loss", patience=5,␣
 ↪restore_best_weights=True,)
checkpointer = ModelCheckpoint(filepath='saved_models/lstm_classification.hdf5',␣
 ↪verbose=1, save_best_only=True)

with tf.device('/device:GPU:0'):
  history = lstm_model.fit(training_data, training_onehot,␣
 ↪batch_size=batch_size, epochs=epochs, validation_data=(validation_data,␣
 ↪validation_onehot), callbacks=[es, checkpointer], verbose=1)
```

```
Epoch 1/200
1557/1559 [============================>.] - ETA: 0s - loss: 2.0928 - accuracy:
0.1842
Epoch 1: val_loss improved from inf to 2.05699, saving model to
saved_models/lstm_classification.hdf5
1559/1559 [==============================] - 10s 5ms/step - loss: 2.0929 -
accuracy: 0.1842 - val_loss: 2.0570 - val_accuracy: 0.1974

Epoch 141: val_loss did not improve from 1.26423
1559/1559 [==============================] - 9s 6ms/step - loss: 1.1837 -
accuracy: 0.5093 - val_loss: 1.2654 - val_accuracy: 0.4751
```

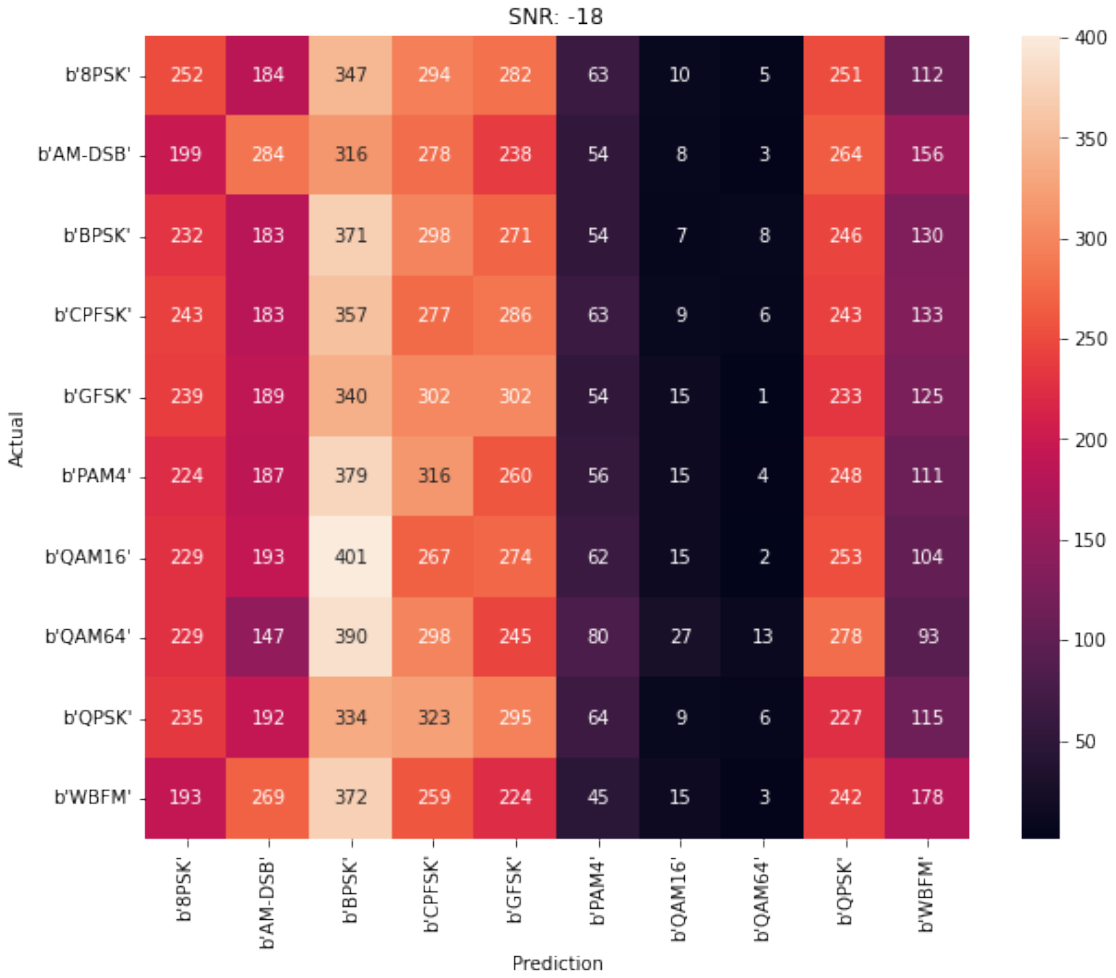
[ ]:
```
plot_model_history(history, 'LSTM Model')
model_scoring(lstm_model, history, testing_data, testing_pair_labels)
```



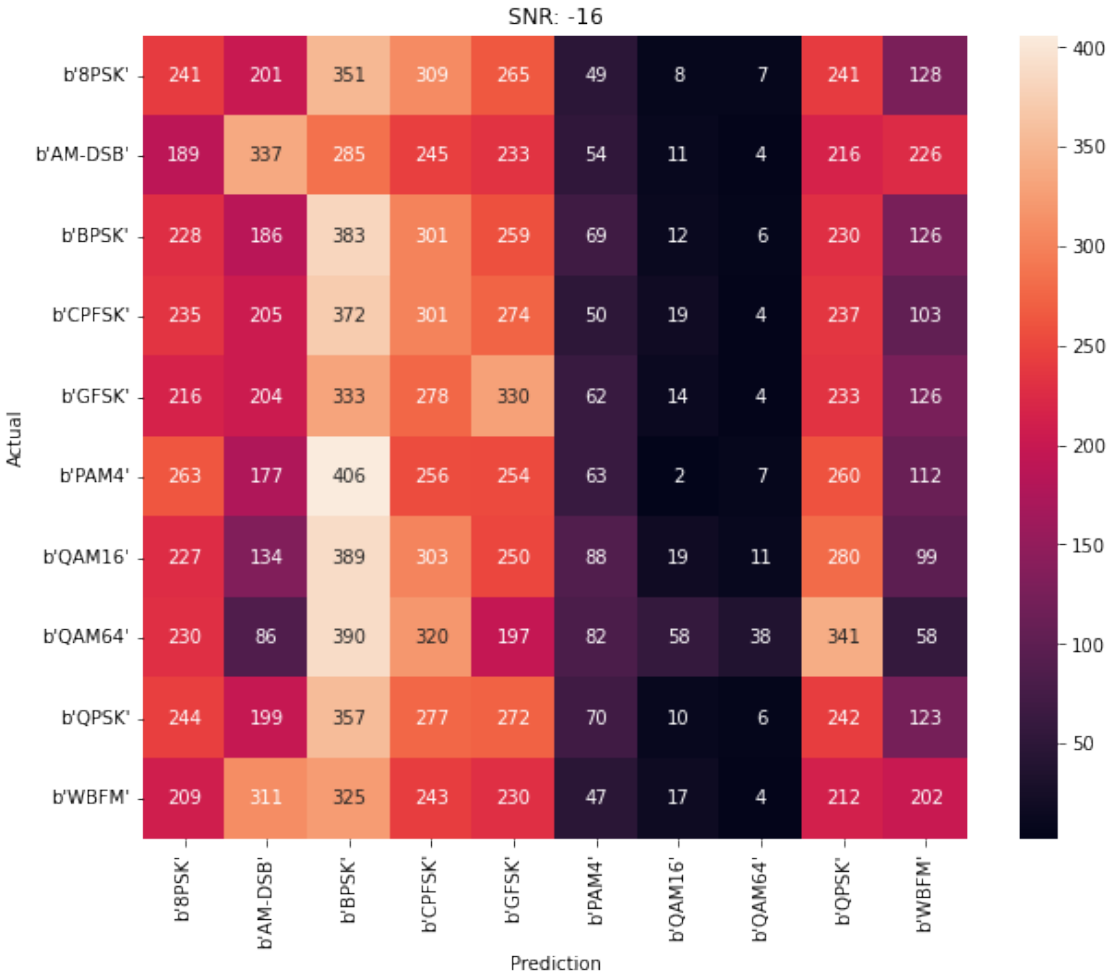

```
Accuracy at SNR = -20 is 0.10622222222222222%
```



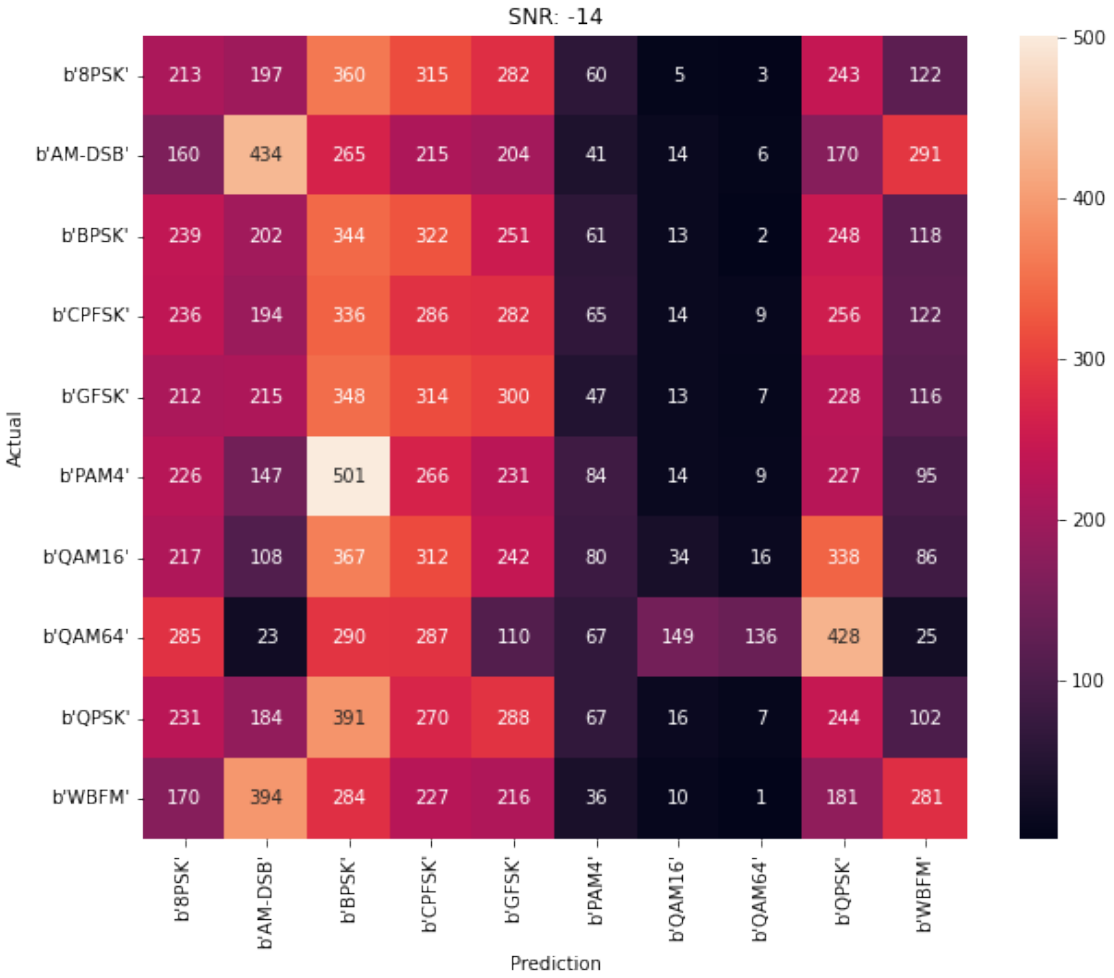

```
Accuracy at SNR = -18 is 0.10972222222222222%
```



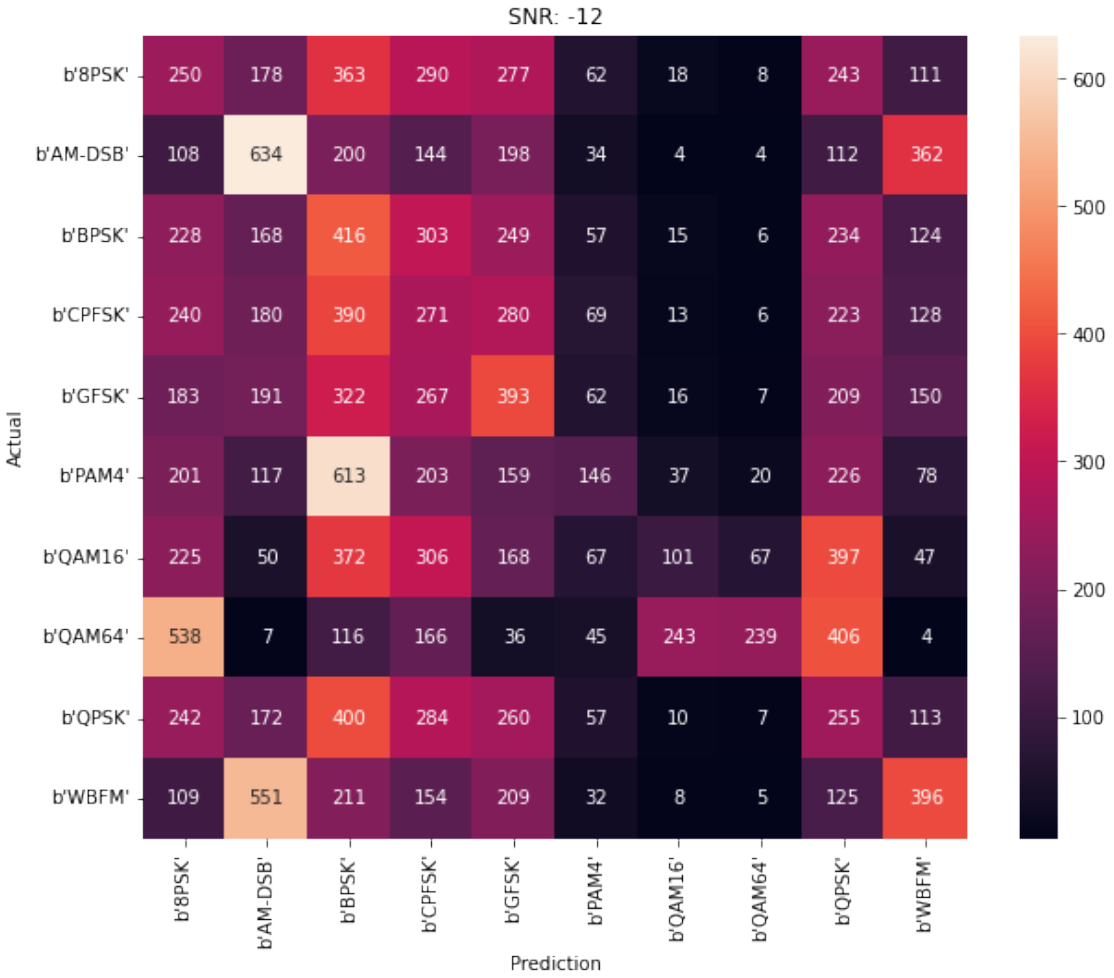

```
Accuracy at SNR = -16 is 0.11977777777777777%
```



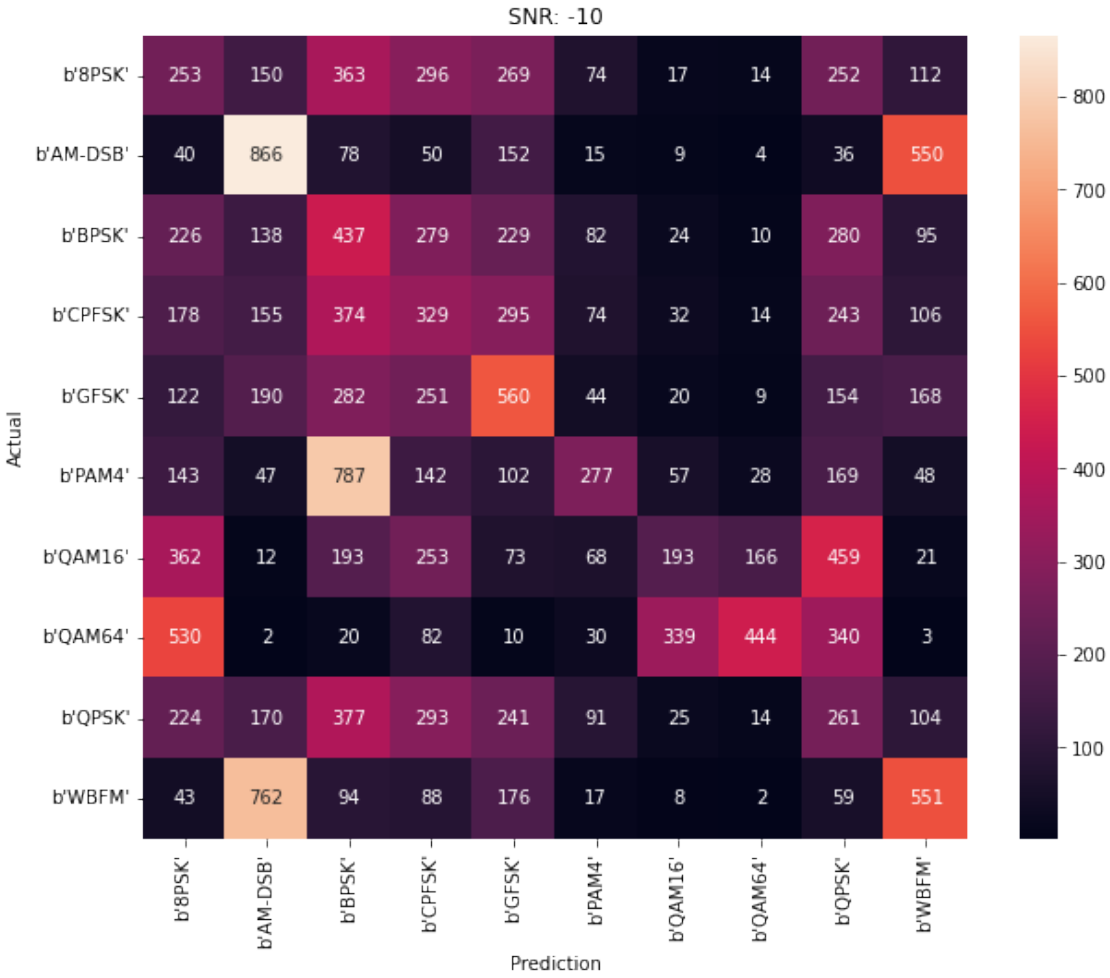

```
Accuracy at SNR = -14 is 0.1308888888888889%
```



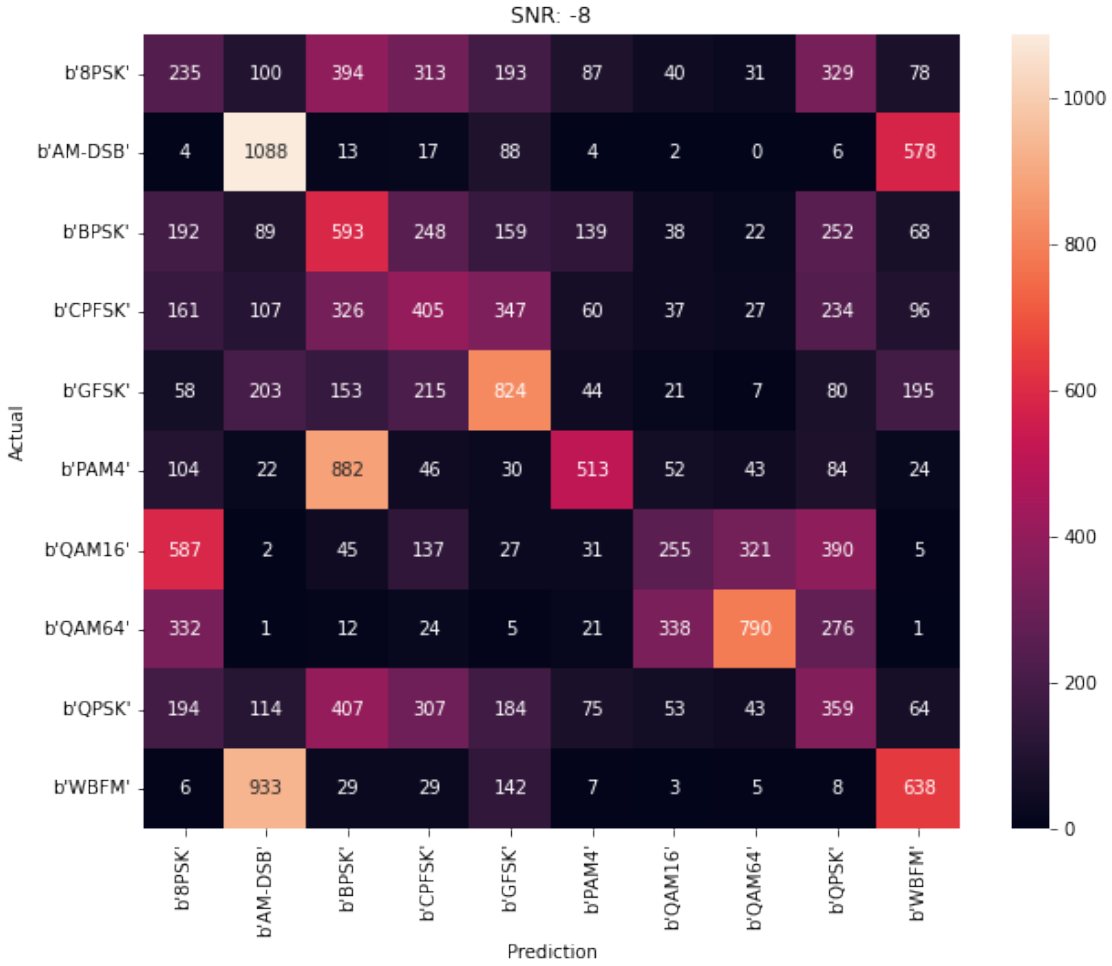

```
Accuracy at SNR = -12 is 0.17227777777777778%
```



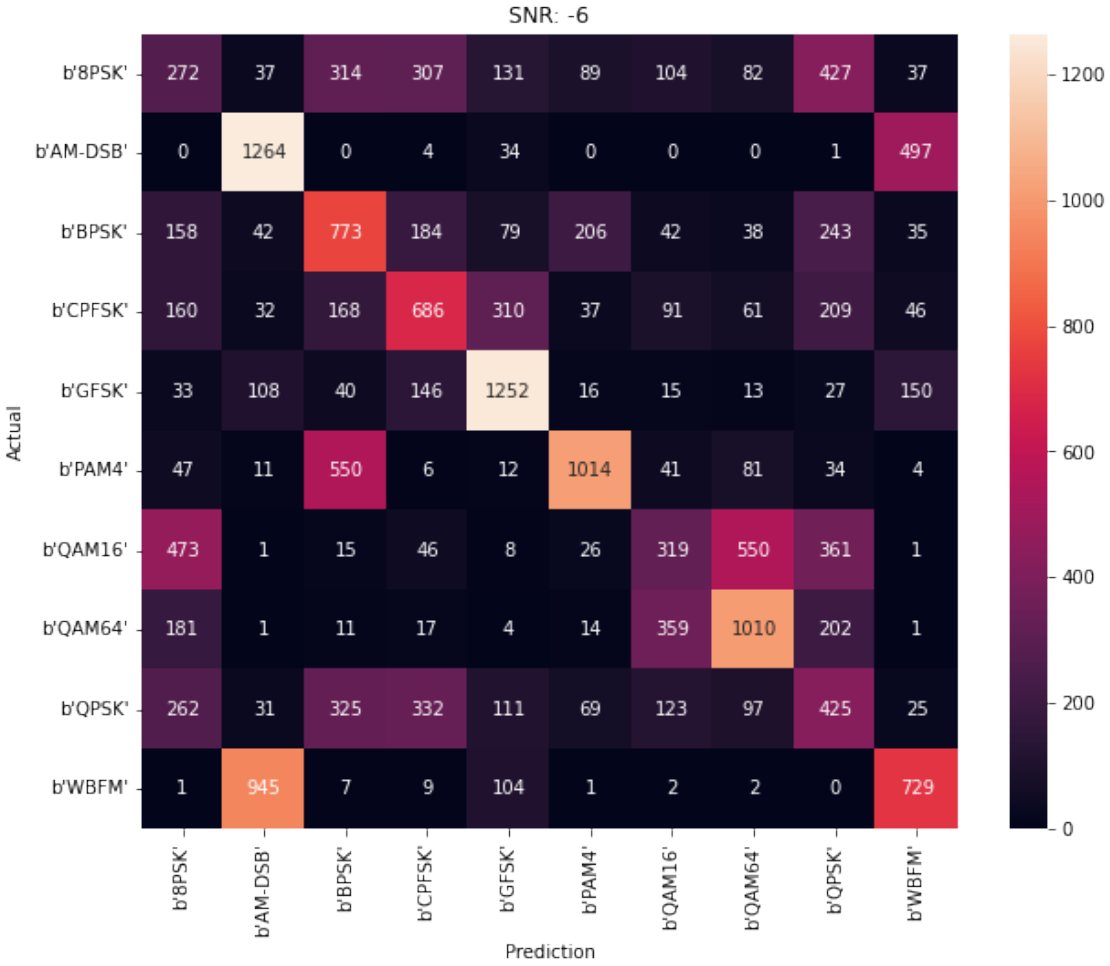

```
Accuracy at SNR = -10 is 0.23172222222222222%
```



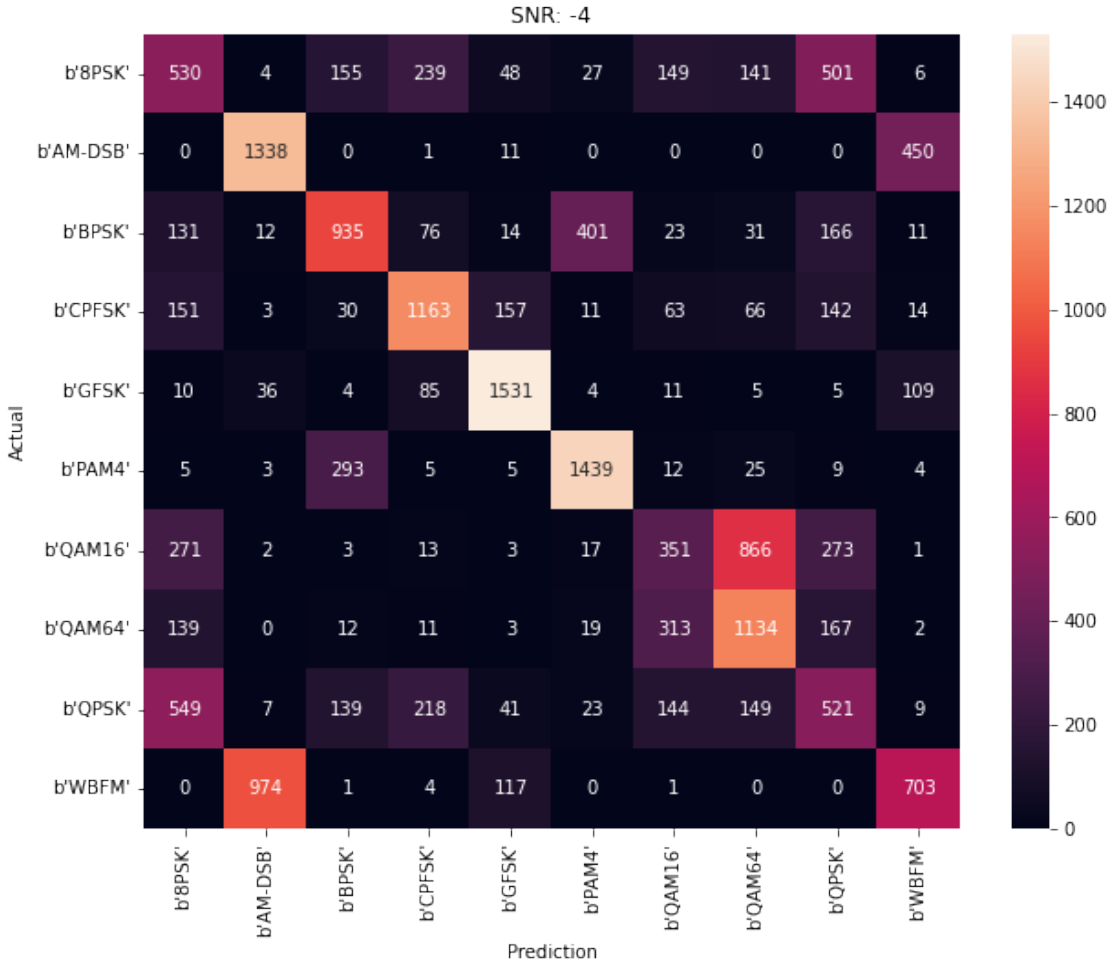

```
Accuracy at SNR = -8 is 0.31666666666666665%
```



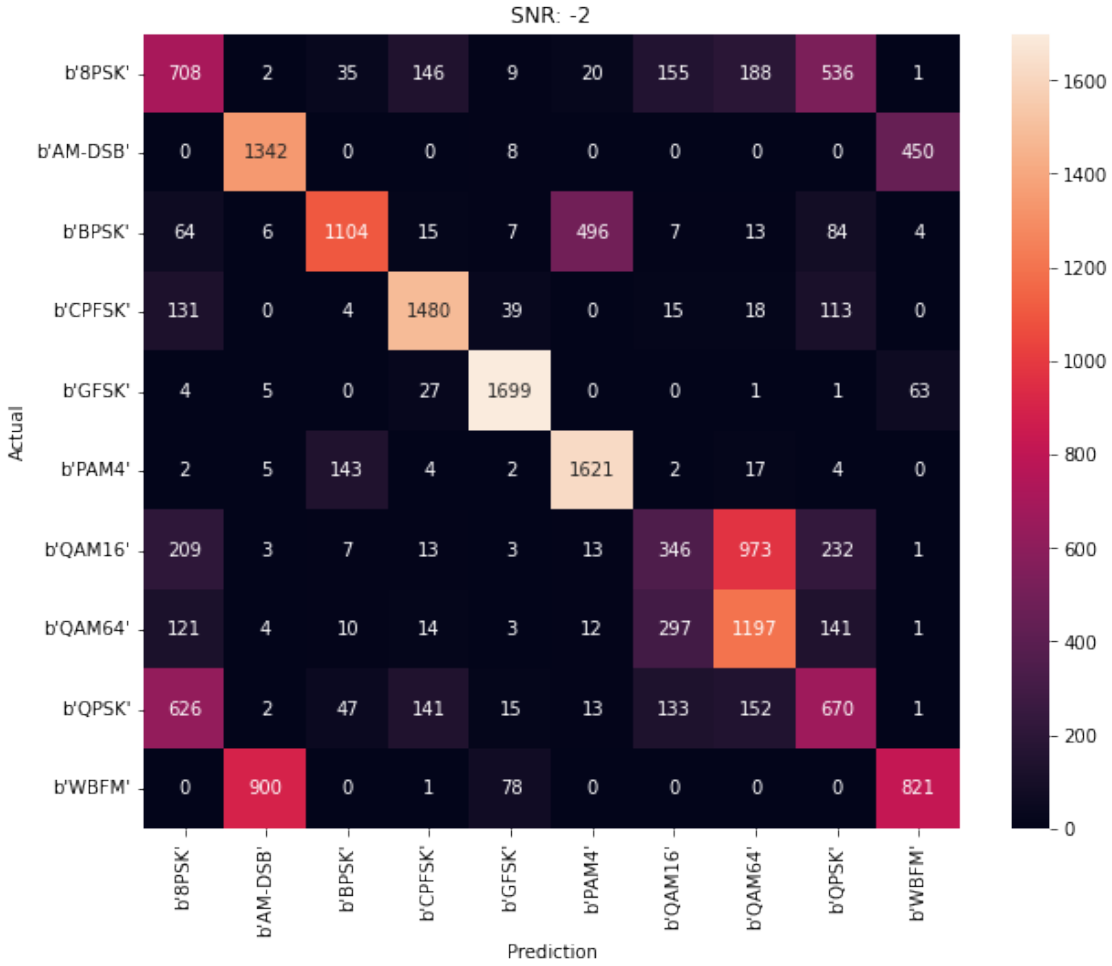

```
Accuracy at SNR = -6 is 0.43022222222222223%
```



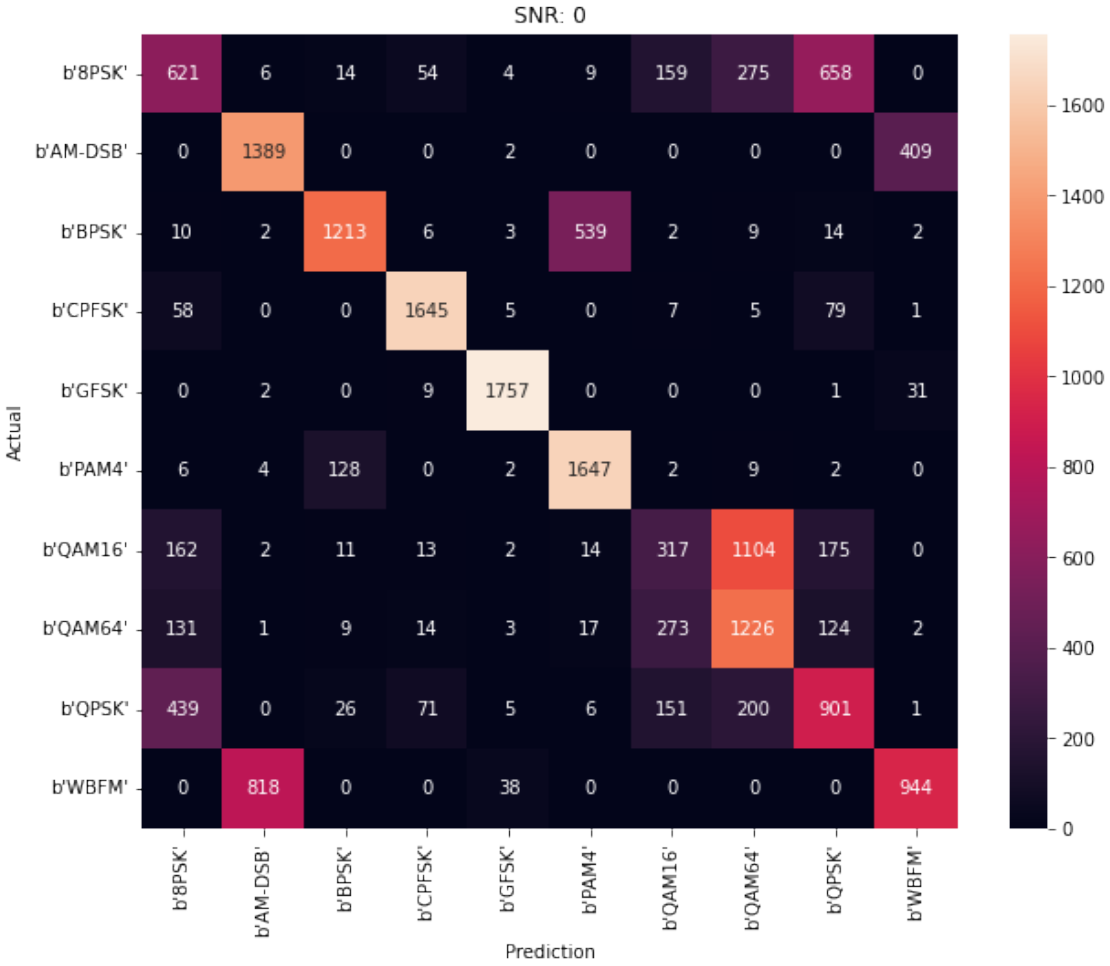

```
Accuracy at SNR = -4 is 0.5358333333333334%
```



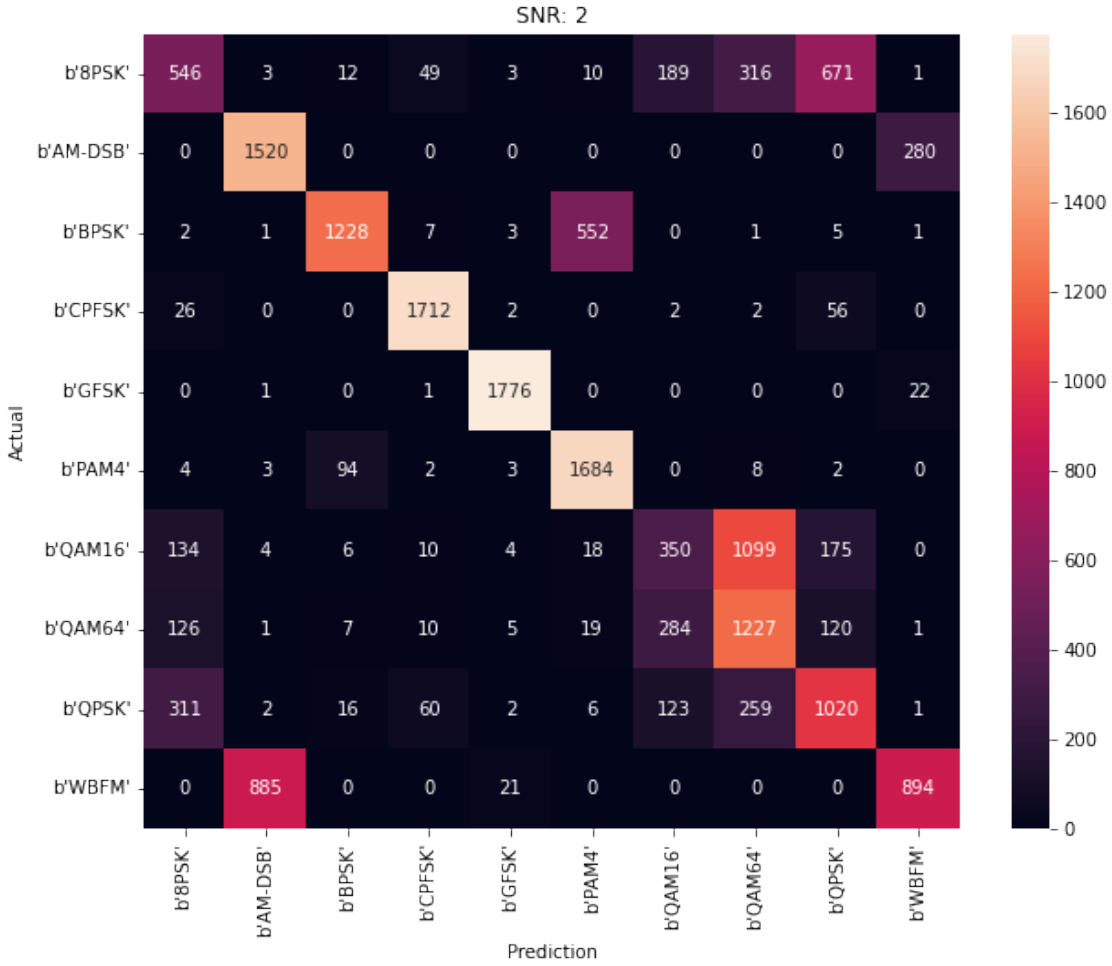

```
Accuracy at SNR = -2 is 0.6104444444444445%
```



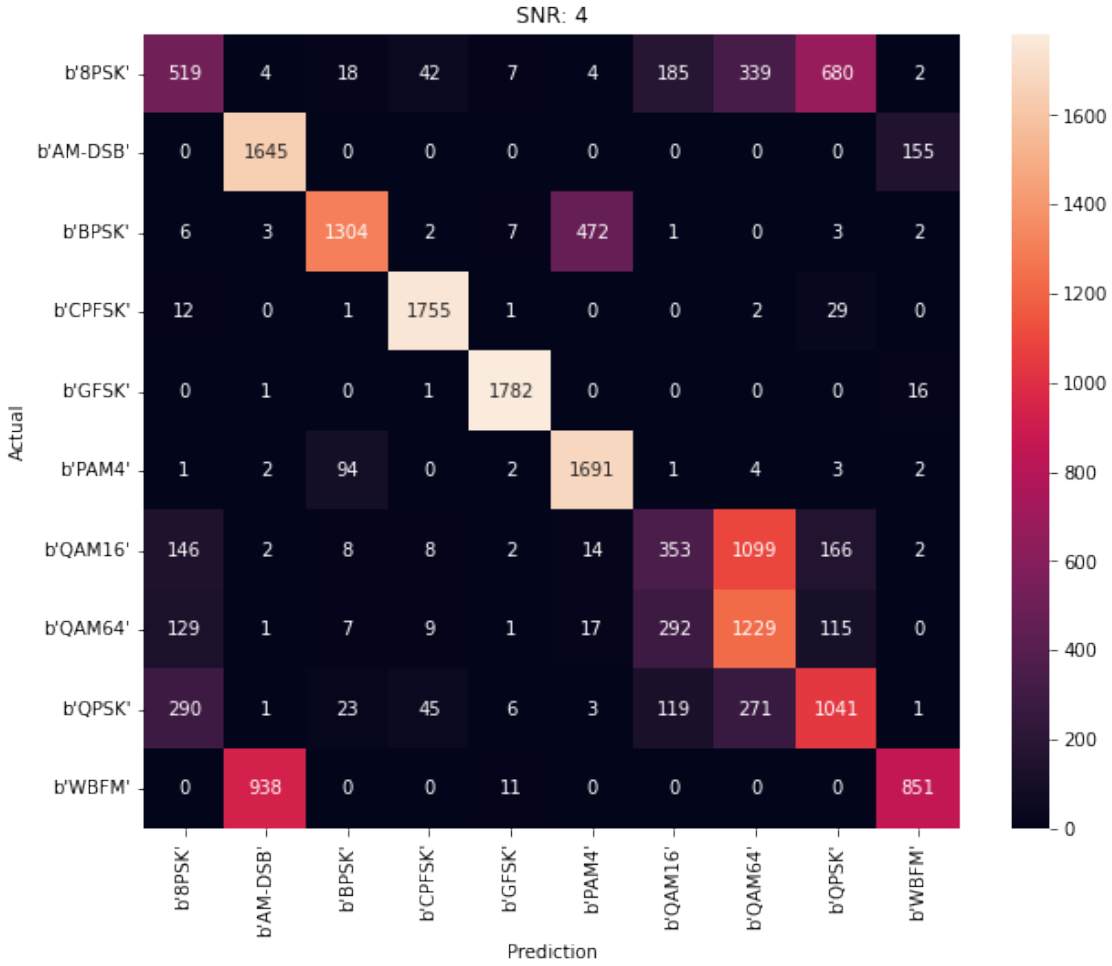

```
Accuracy at SNR = 0 is 0.6477777777777778%
```



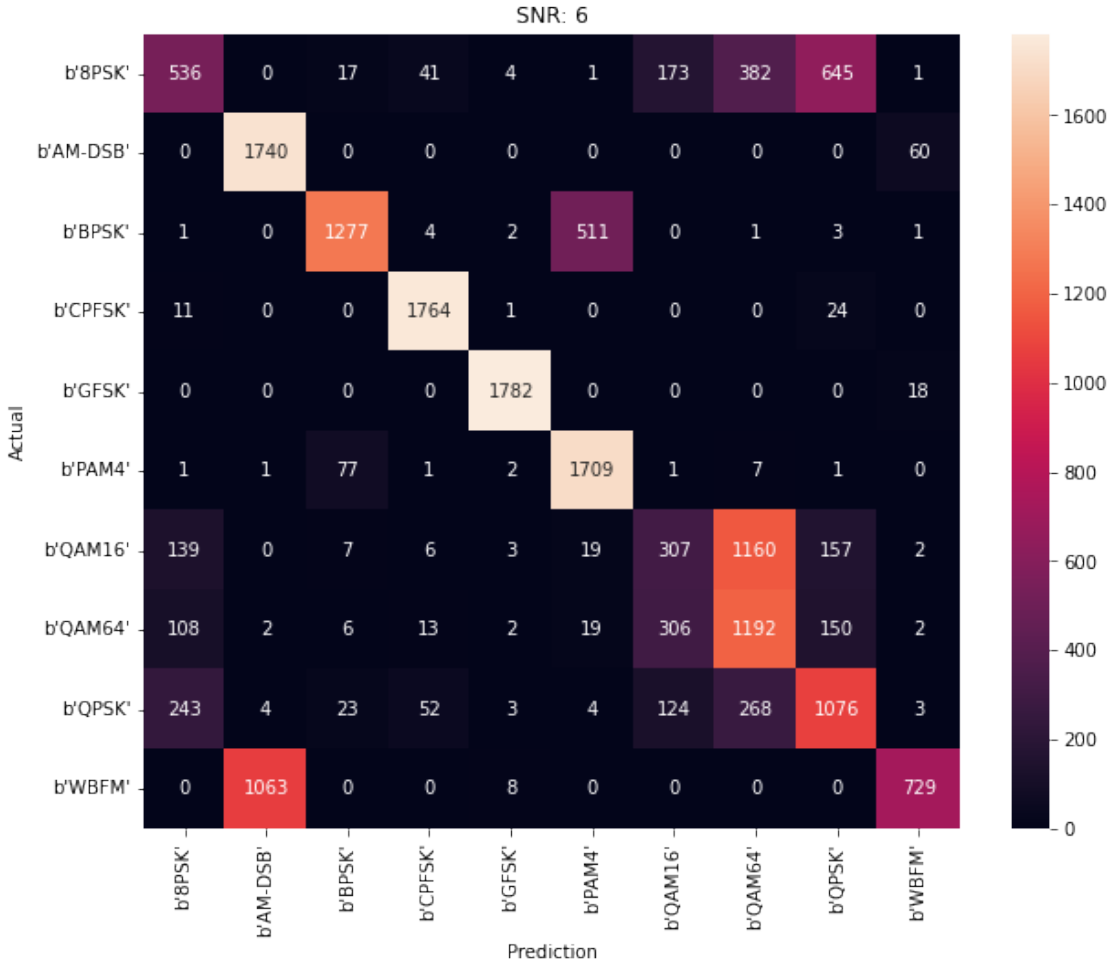

```
Accuracy at SNR = 2 is 0.6642777777777777%
```



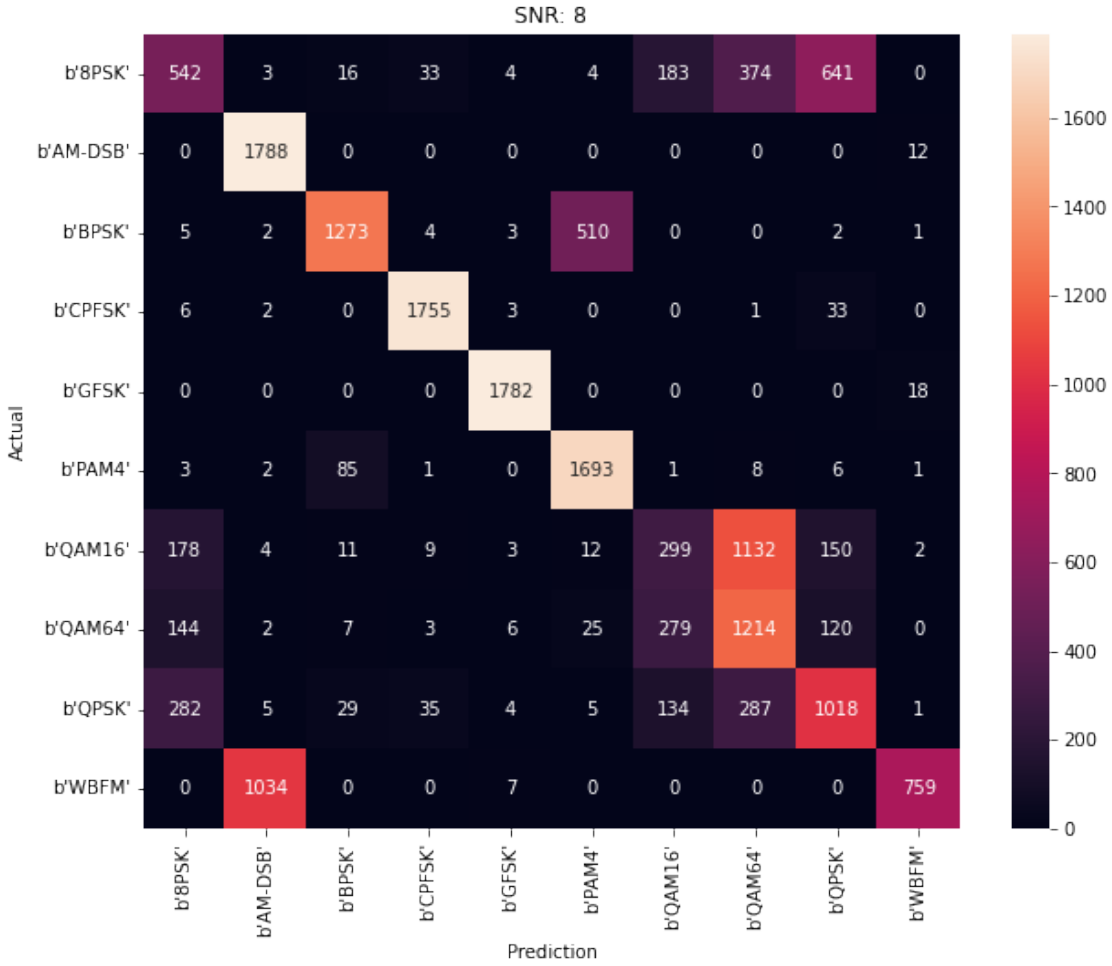
Accuracy at SNR = 4 is 0.6761111111111111%



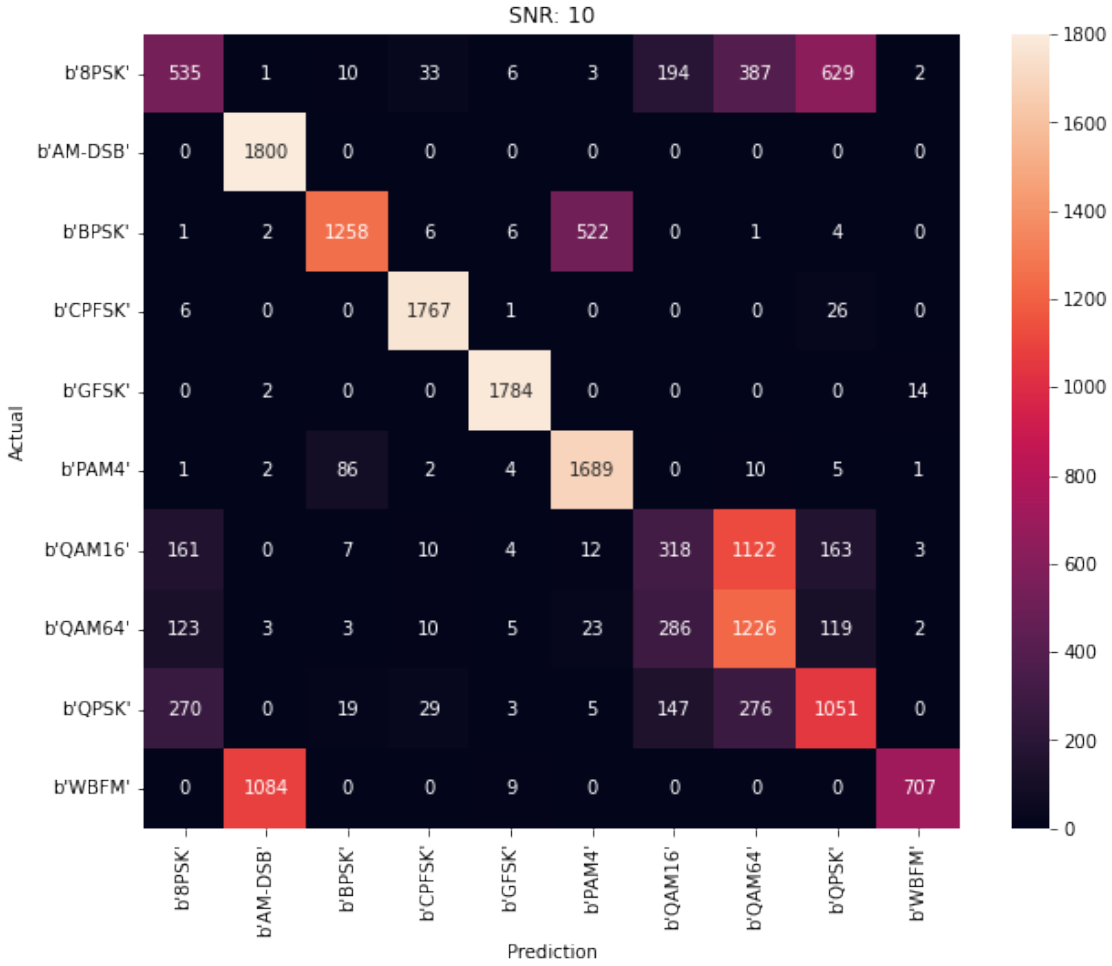
Accuracy at SNR = 6 is 0.6728888888888889%



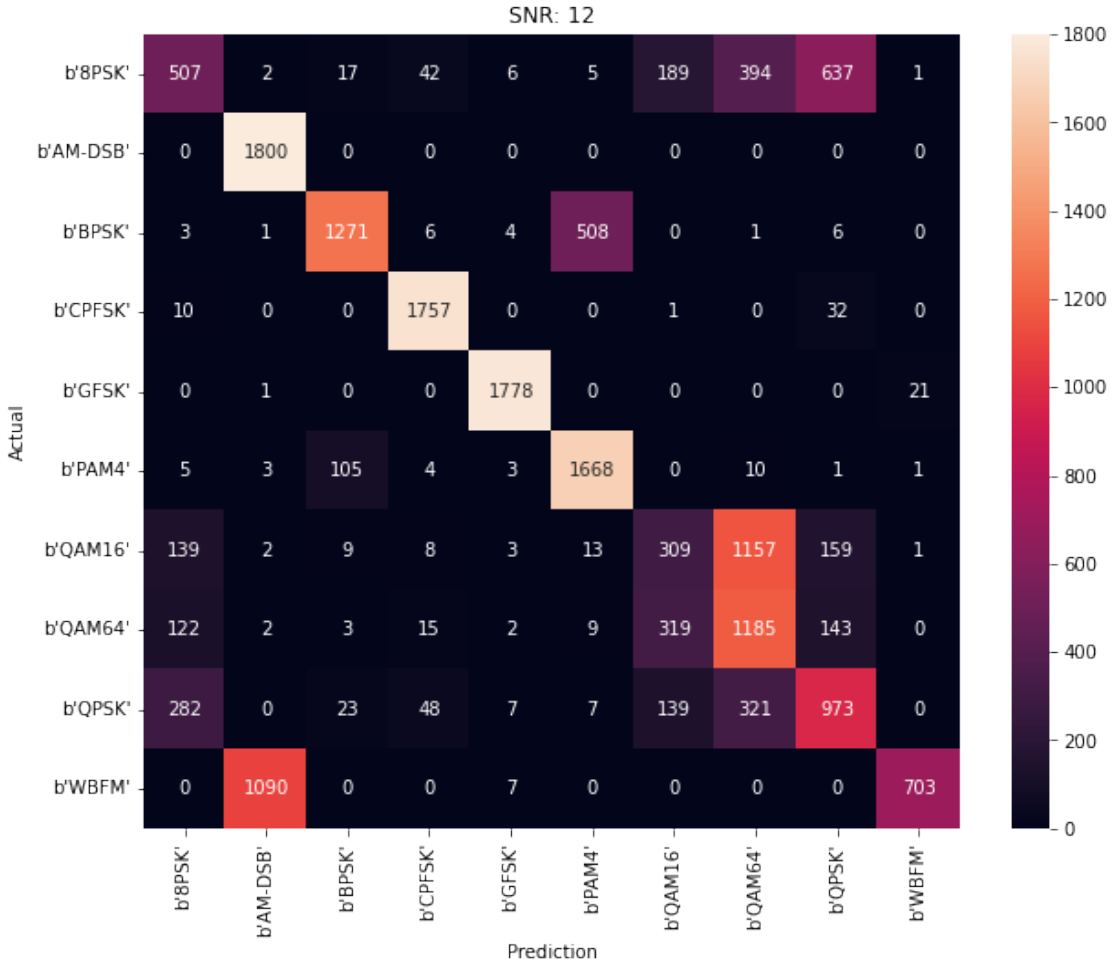

```
Accuracy at SNR = 8 is 0.6735%
```



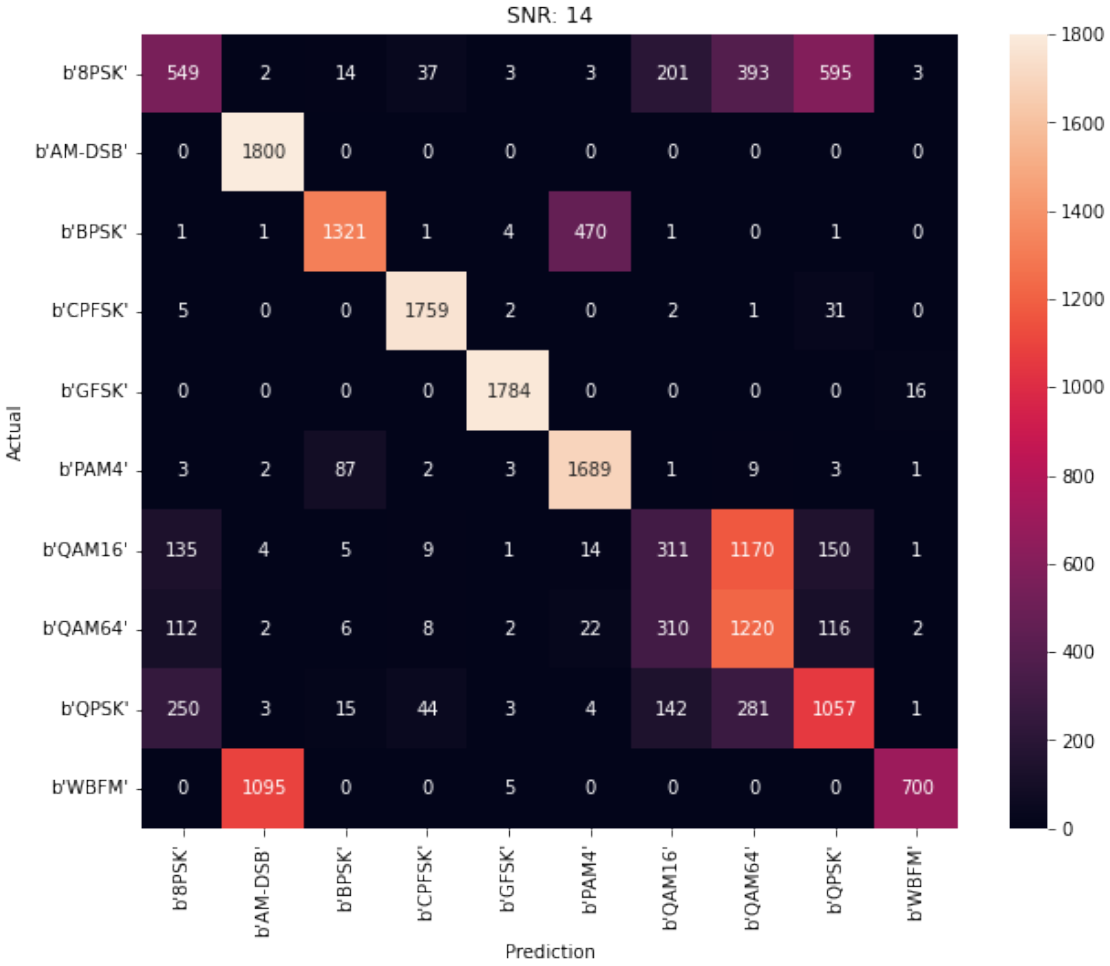

```
Accuracy at SNR = 10 is 0.6741666666666667%
```



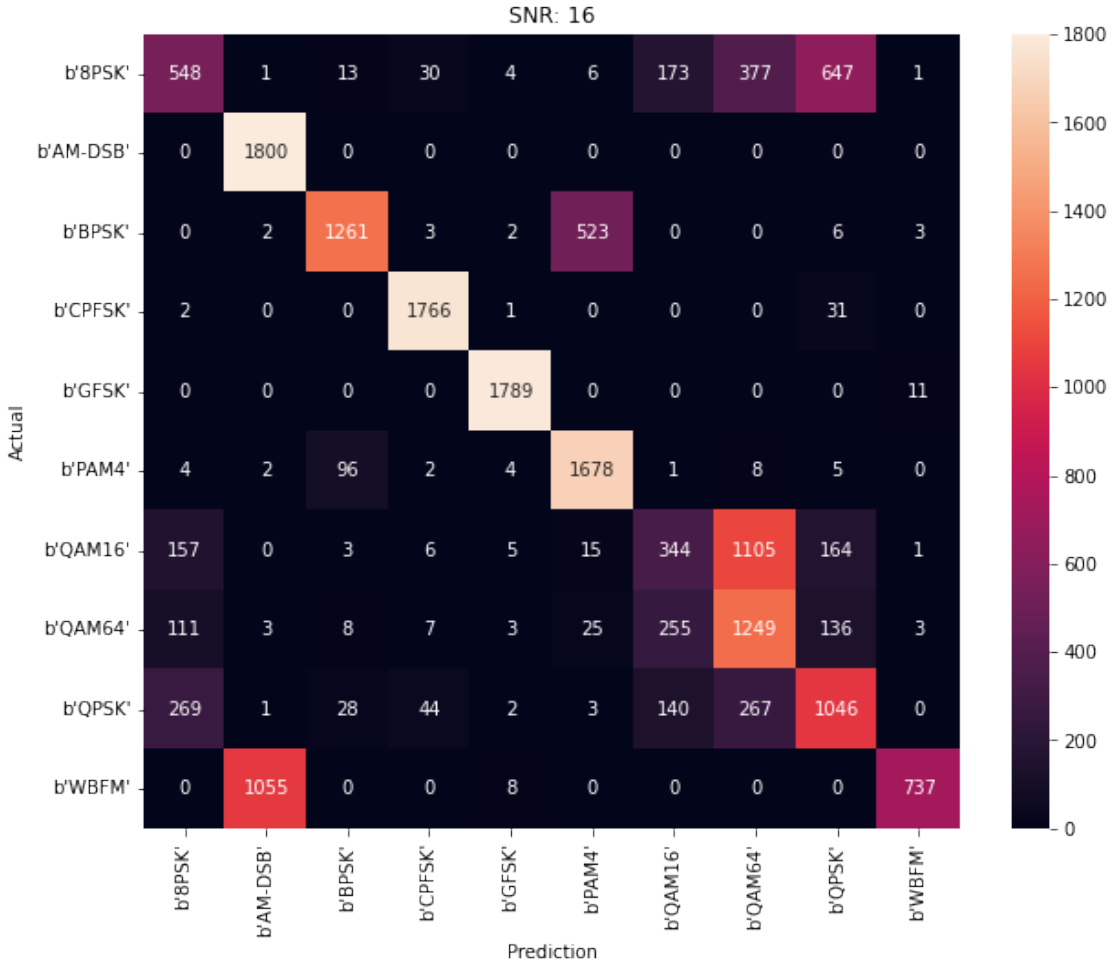

```
Accuracy at SNR = 12 is 0.6639444444444444%
```



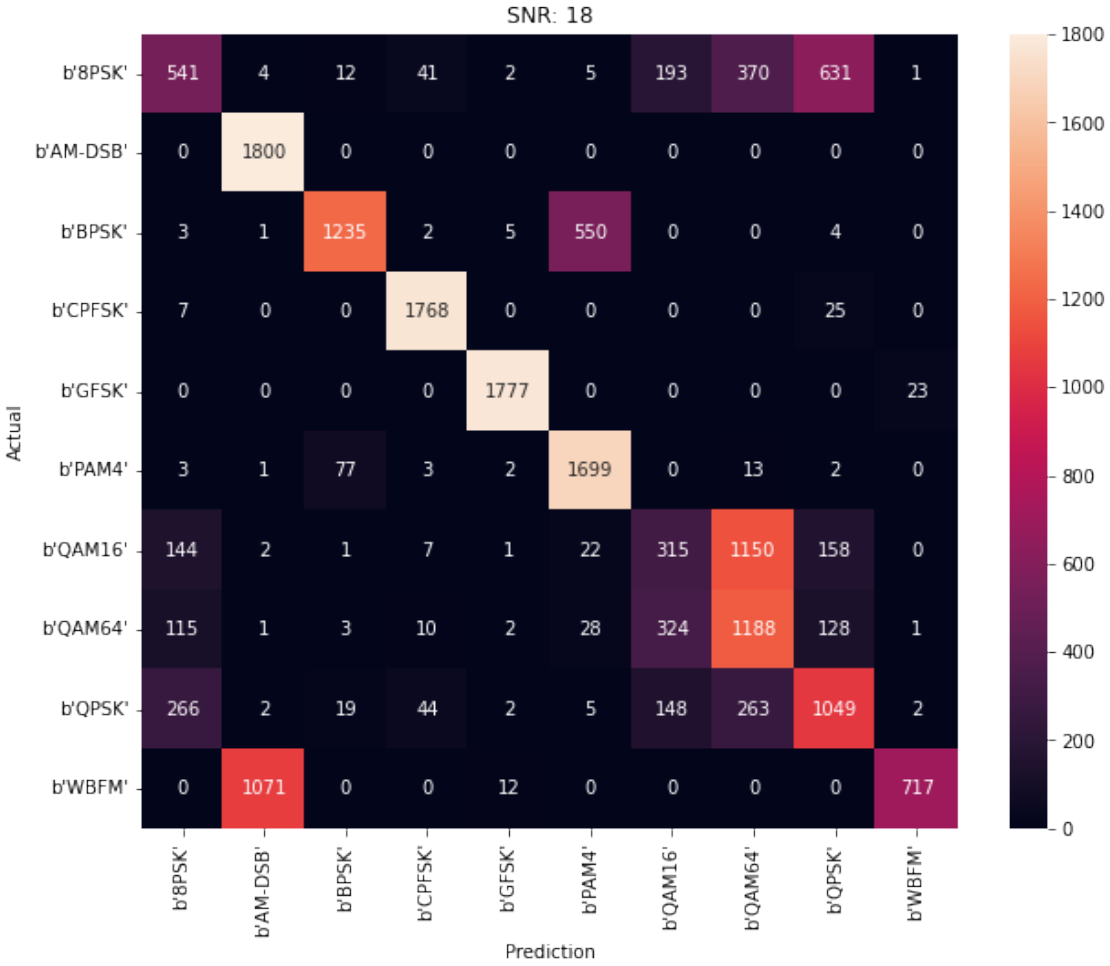
Accuracy at SNR = 14 is 0.6772222222222222%

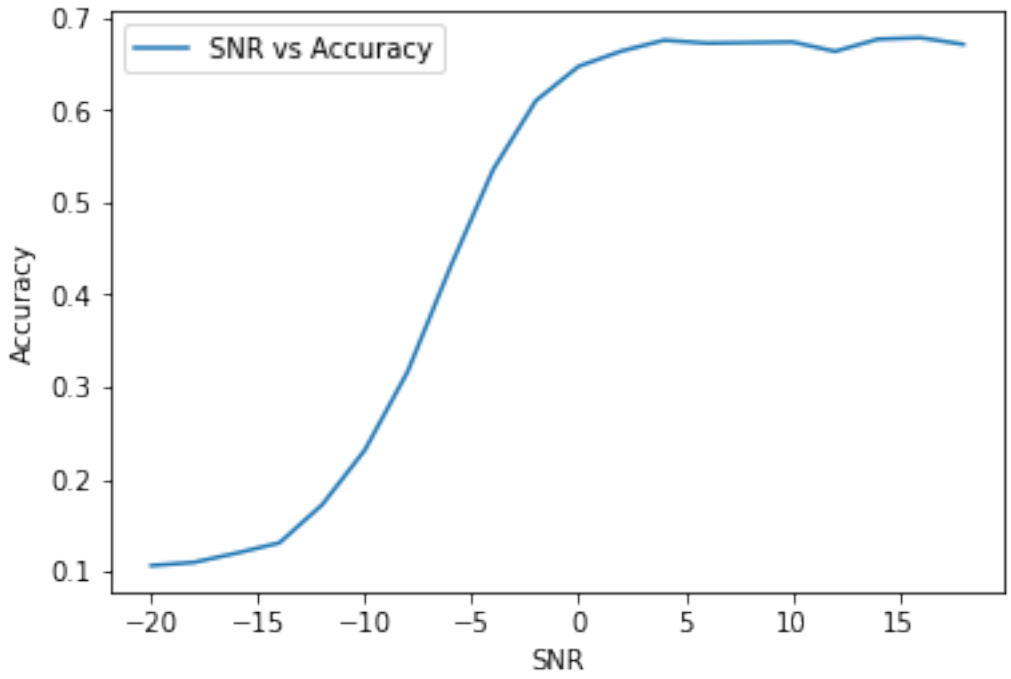



```
Accuracy at SNR = 16 is 0.6787777777777778%
```




```
Accuracy at SNR = 18 is 0.6716111111111112%
```


SNR: 18
b'8PSK' 541 4 12 41 2 5 193 370 631 1
b'AM-DSB' 0 1800 0 0 0 0 0 0 0 0
b'BPSK' 3 1 1235 2 5 550 0 0 4 0
b'CPFSK' 7 0 0 1768 0 0 0 0 25 0
b'GFSK' 0 0 0 0 1777 0 0 0 0 23
b'PAM4' 3 1 77 3 2 1699 0 13 2 0
b'QAM16' 144 2 1 7 1 22 315 1150 158 0
b'QAM64' 115 1 3 10 2 28 324 1188 128 1
b'QPSK' 266 2 19 44 2 5 148 263 1049 2
b'WBFM' 0 1071 0 0 12 0 0 0 0 717
Actual
b'8PSK' b'AM-DSB' b'BPSK' b'CPFSK' b'GFSK' b'PAM4' b'QAM16' b'QAM64' b'QPSK' b'WBFM'
Prediction
1800 1600 1400 1200 1000 800 600 400 200 0



7 Differentiated Features Space

[27]:
```
fdit_training_data = np.concatenate((normalize(np.gradient(training_data[:,0],␣
 ↪axis = 1)), normalize(np.gradient(training_data[:,1], axis = 1))), axis=1).
 ↪reshape(training_data.shape)
fdit_validation_data = np.concatenate((normalize(np.gradient(validation_data[:
 ↪,0], axis = 1)), normalize(np.gradient(validation_data[:,1], axis = 1))),␣
 ↪axis=1).reshape(validation_data.shape)
fdit_testing_data = np.concatenate((normalize(np.gradient(testing_data[:,0],␣
 ↪axis = 1)), normalize(np.gradient(testing_data[:,1], axis = 1))), axis=1).
 ↪reshape(testing_data.shape)
```

[28]:
```
print('fdit training data shape:', fdit_training_data.shape)
print('fdit validation data shape:', fdit_validation_data.shape)
print('fdit testing data shape:', fdit_testing_data.shape)
```

```
fdit training data shape: (798000, 2, 128)
fdit validation data shape: (42000, 2, 128)
fdit testing data shape: (360000, 2, 128)
```

7.1 CNN Model

[ ]:
```
fdit_training_data, fdit_validation_data, fdit_testing_data =␣
↪reshape_data_for_cnn(fdit_training_data, fdit_validation_data,␣
↪fdit_testing_data)
```

[ ]:
```
print('training data shape:', fdit_training_data.shape)
print('validation data shape:', fdit_validation_data.shape)
print('testing data shape:', fdit_testing_data.shape)
```

```
training data shape: (798000, 2, 128, 1)
validation data shape: (42000, 2, 128, 1)
testing data shape: (360000, 2, 128, 1)
```

[ ]:
```
learning_rate = 0.001
batch_size = 512
epochs = 200
```

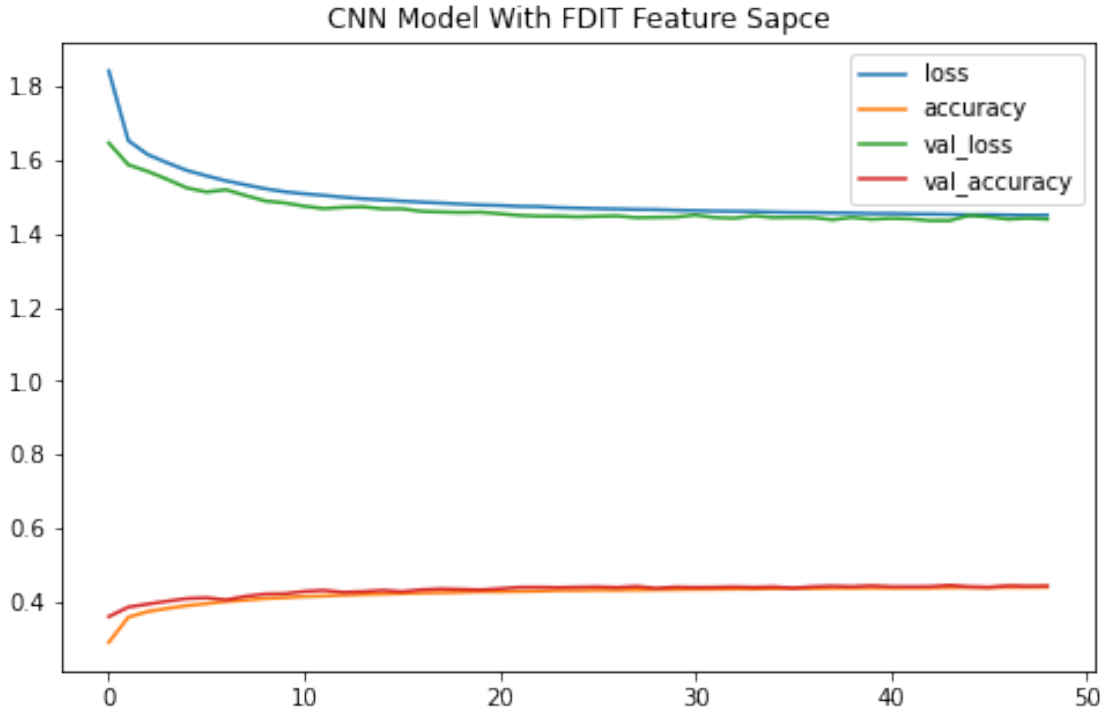
[ ]:
```
cnn_model = Sequential()
cnn_model.add(Conv2D(256, 3, activation='relu', padding='same'))
cnn_model.add(Dropout(0.5))
cnn_model.add(Conv2D(64, 3, strides=2, activation='relu', padding='same'))
cnn_model.add(Dropout(0.5))
cnn_model.add(Flatten())
cnn_model.add(Dense(128, activation='relu' ))
cnn_model.add(Dense(10,  activation='softmax'))
cnn_model.compile(loss=tf.keras.losses.CategoricalCrossentropy(),␣
↪metrics='accuracy', optimizer=tf.keras.optimizers.
↪Adam(learning_rate=learning_rate))
```

[ ]:
```
es = tf.keras.callbacks.EarlyStopping(monitor="val_loss", patience=5,␣
↪restore_best_weights=True,)
checkpointer = ModelCheckpoint(filepath='saved_models/cnn_fdit_classification.
↪hdf5', verbose=1, save_best_only=True)

with tf.device('/device:GPU:0'):
  history = cnn_model.fit(fdit_training_data, training_onehot,␣
↪batch_size=batch_size, epochs=epochs, validation_data=(fdit_validation_data,␣
↪validation_onehot), callbacks=[es, checkpointer], verbose=1)
```

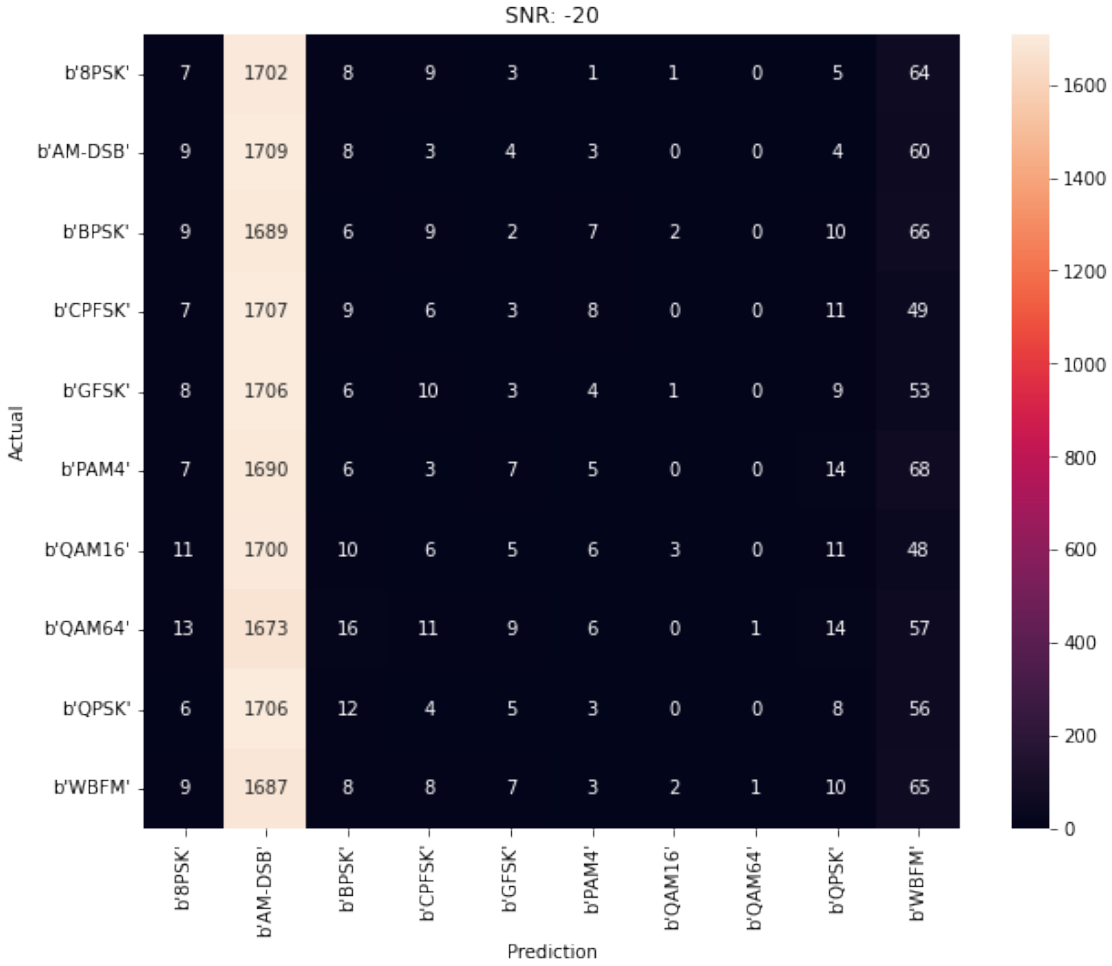
```
Epoch 1/200
1559/1559 [==============================] - ETA: 0s - loss: 1.8433 - accuracy:
0.2877
Epoch 1: val_loss improved from inf to 1.64716, saving model to
saved_models/cnn_fdit_classification.hdf5
1559/1559 [==============================] - 64s 41ms/step - loss: 1.8433 -
accuracy: 0.2877 - val_loss: 1.6472 - val_accuracy: 0.3578
```

```
Epoch 49: val_loss did not improve from 1.43562
1559/1559 [==============================] - 63s 41ms/step - loss: 1.4503 -
accuracy: 0.4382 - val_loss: 1.4397 - val_accuracy: 0.4412
```

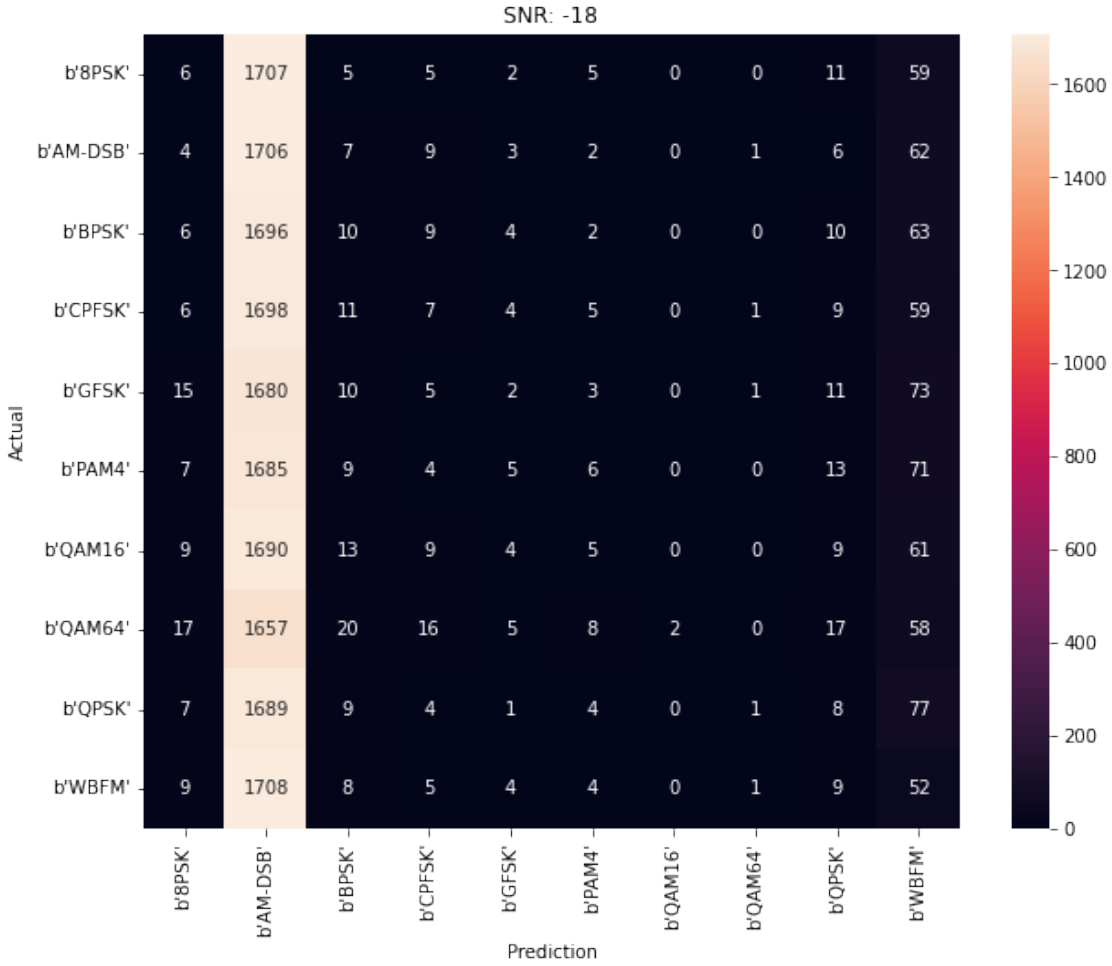
[ ]:
```
plot_model_history(history, 'CNN Model With FDIT Feature Sapce')
model_scoring(cnn_model, history, fdit_testing_data, testing_pair_labels)
```



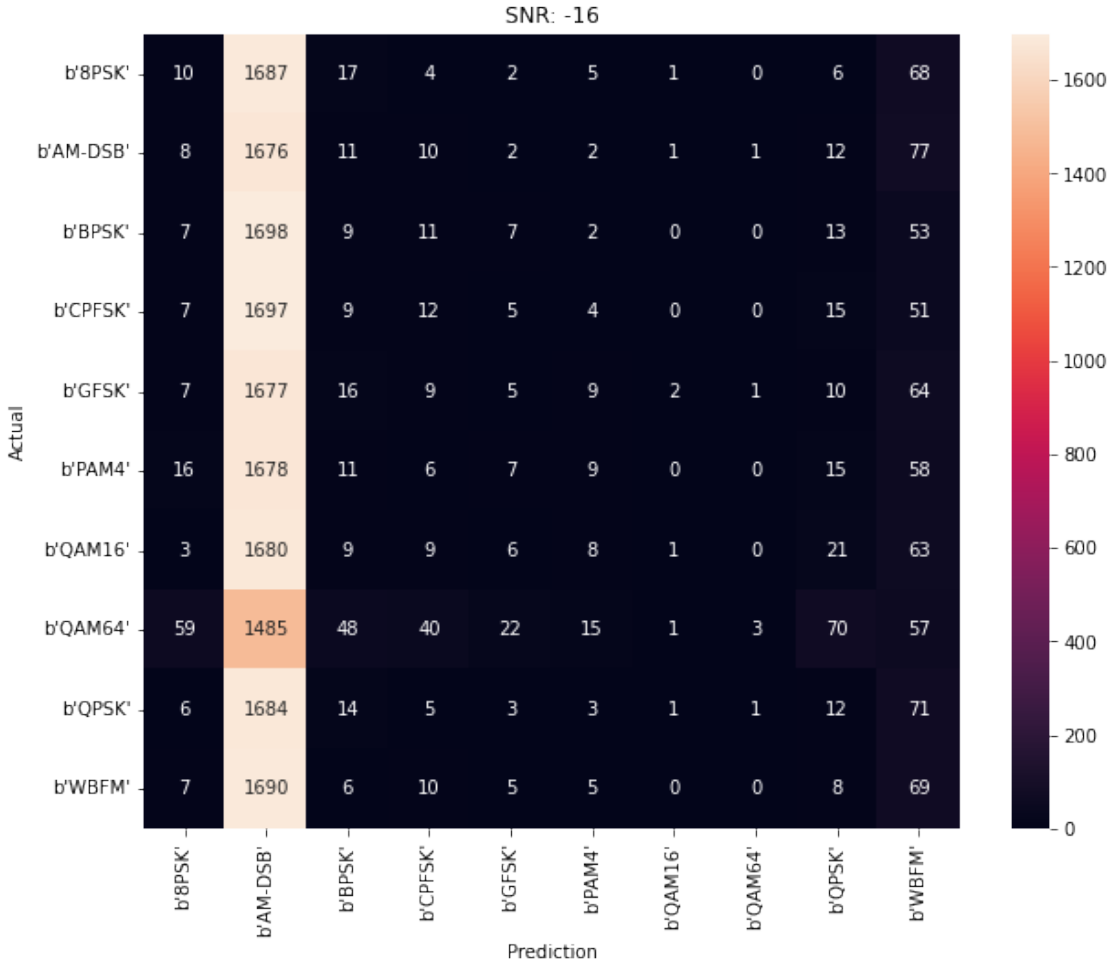

```
Accuracy at SNR = -20 is 0.10072222222222223%
```



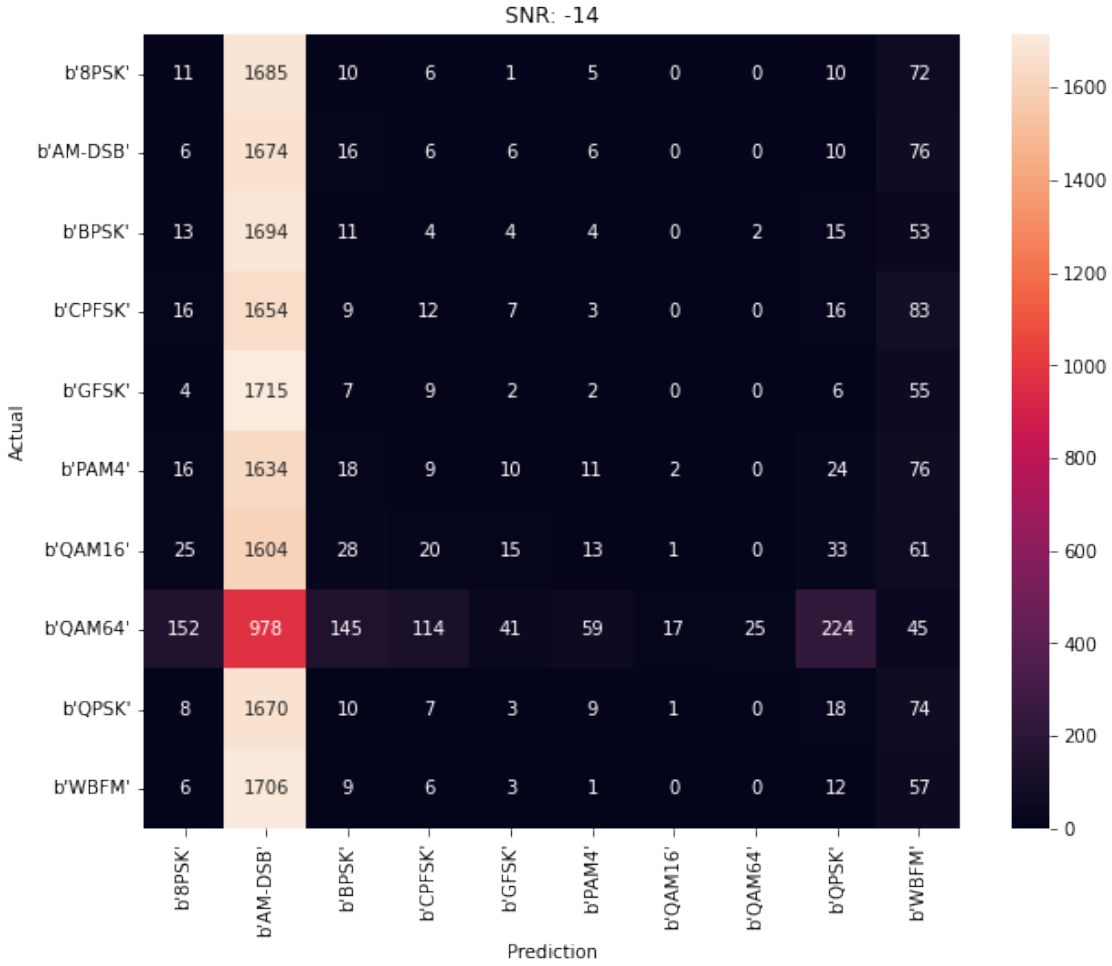

```
Accuracy at SNR = -18 is 0.09983333333333333%
```



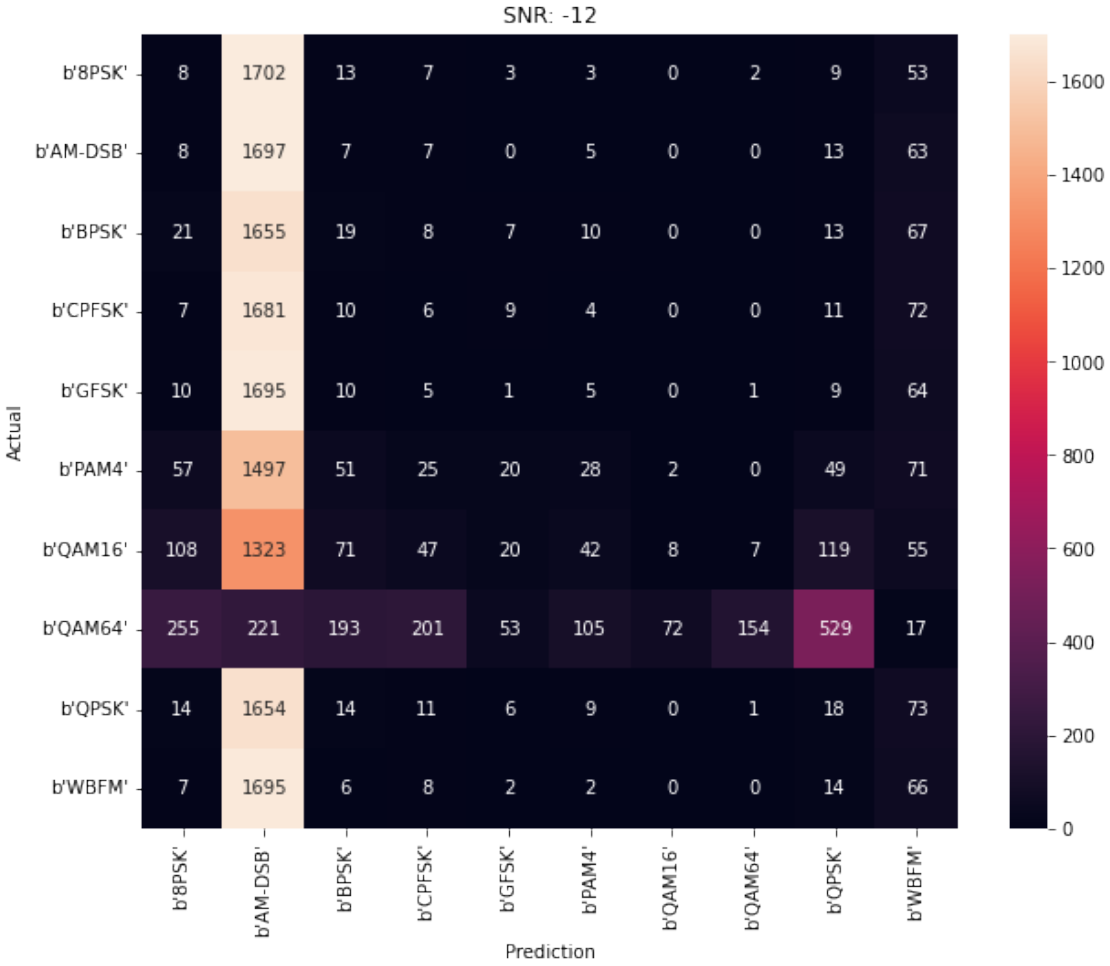

```
Accuracy at SNR = -16 is 0.10033333333333333%
```



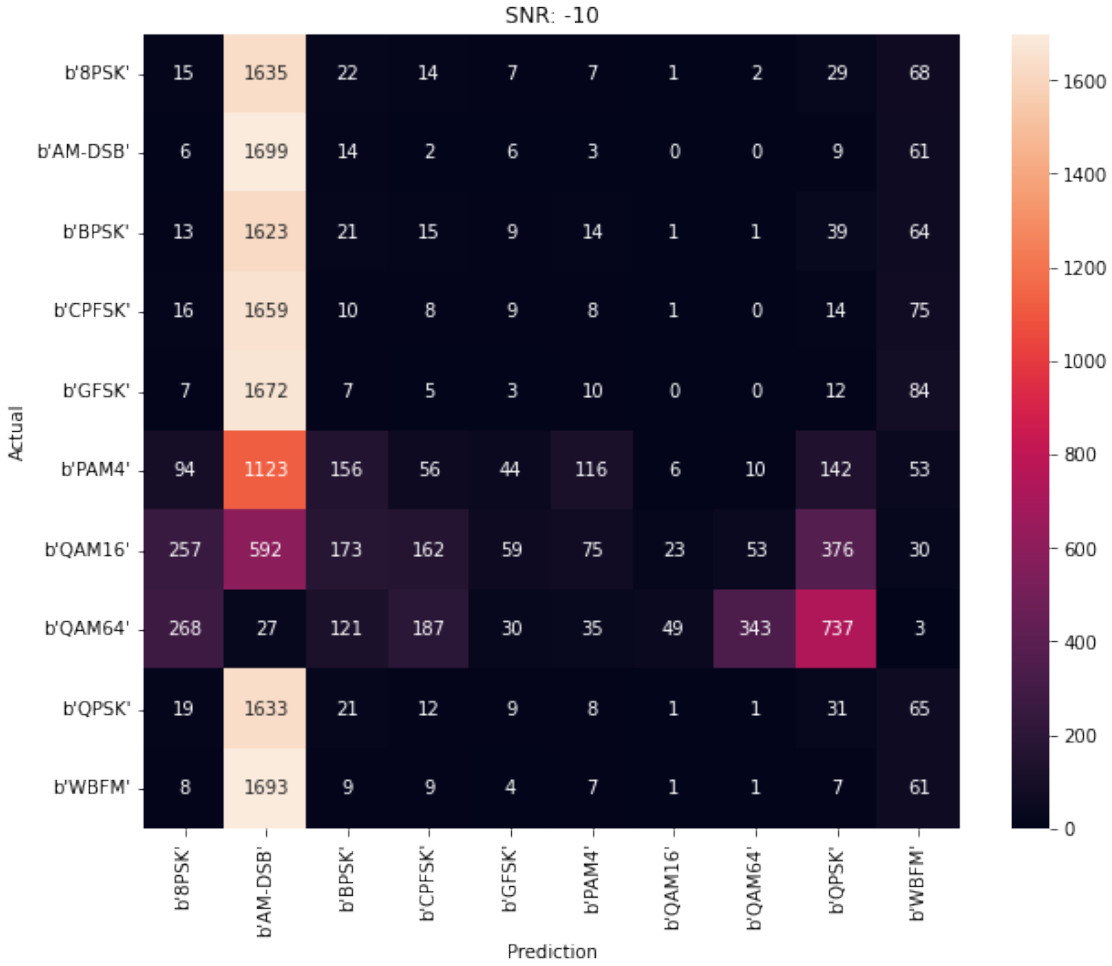

```
Accuracy at SNR = -14 is 0.10122222222222223%
```



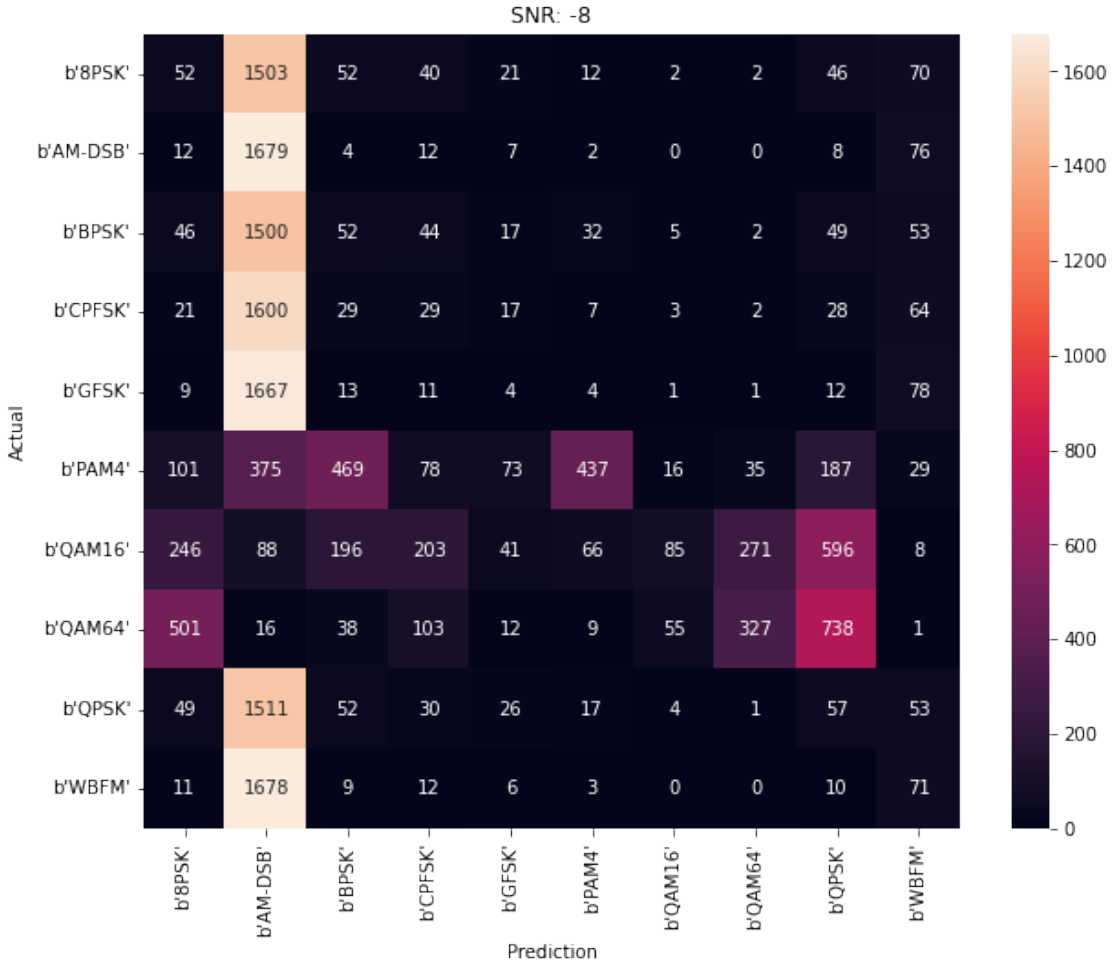

```
Accuracy at SNR = -12 is 0.11138888888888888%
```



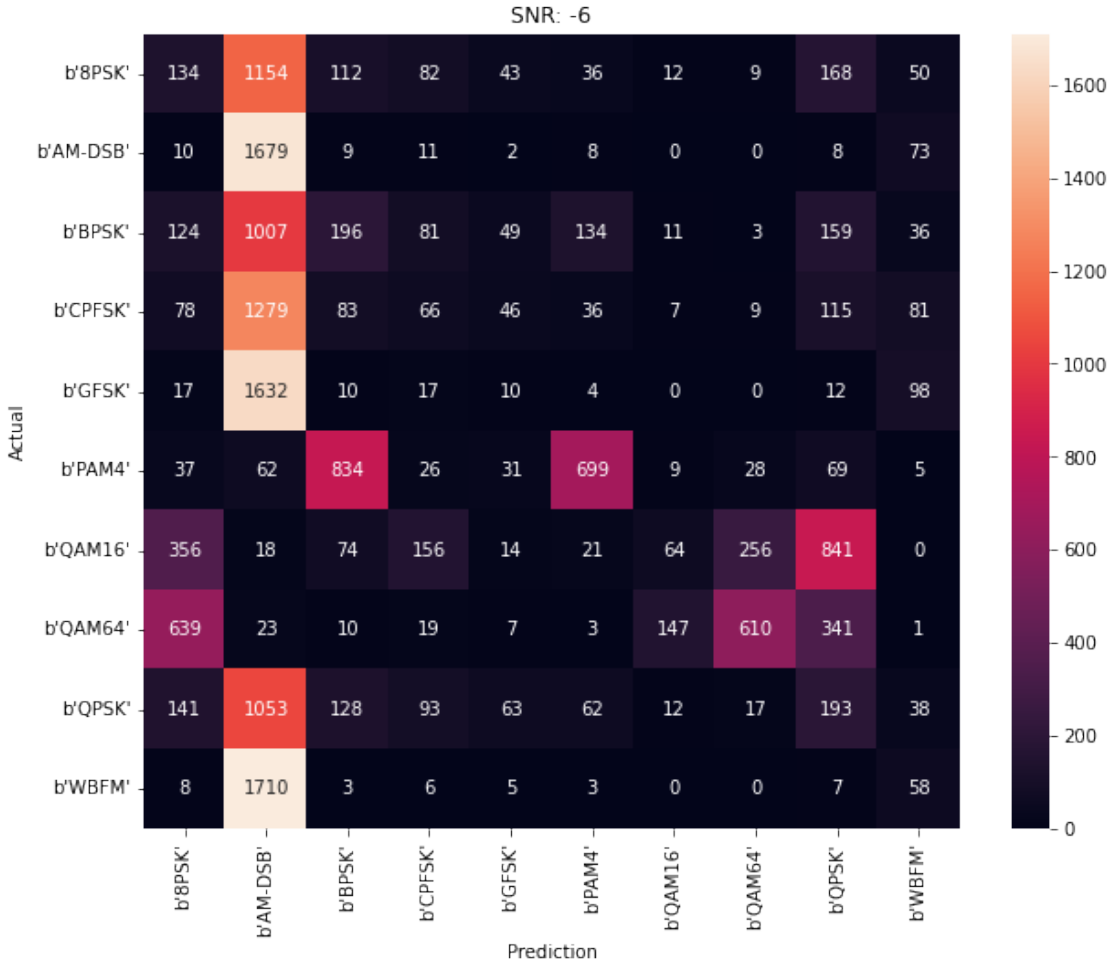

```
Accuracy at SNR = -10 is 0.1288888888888889%
```



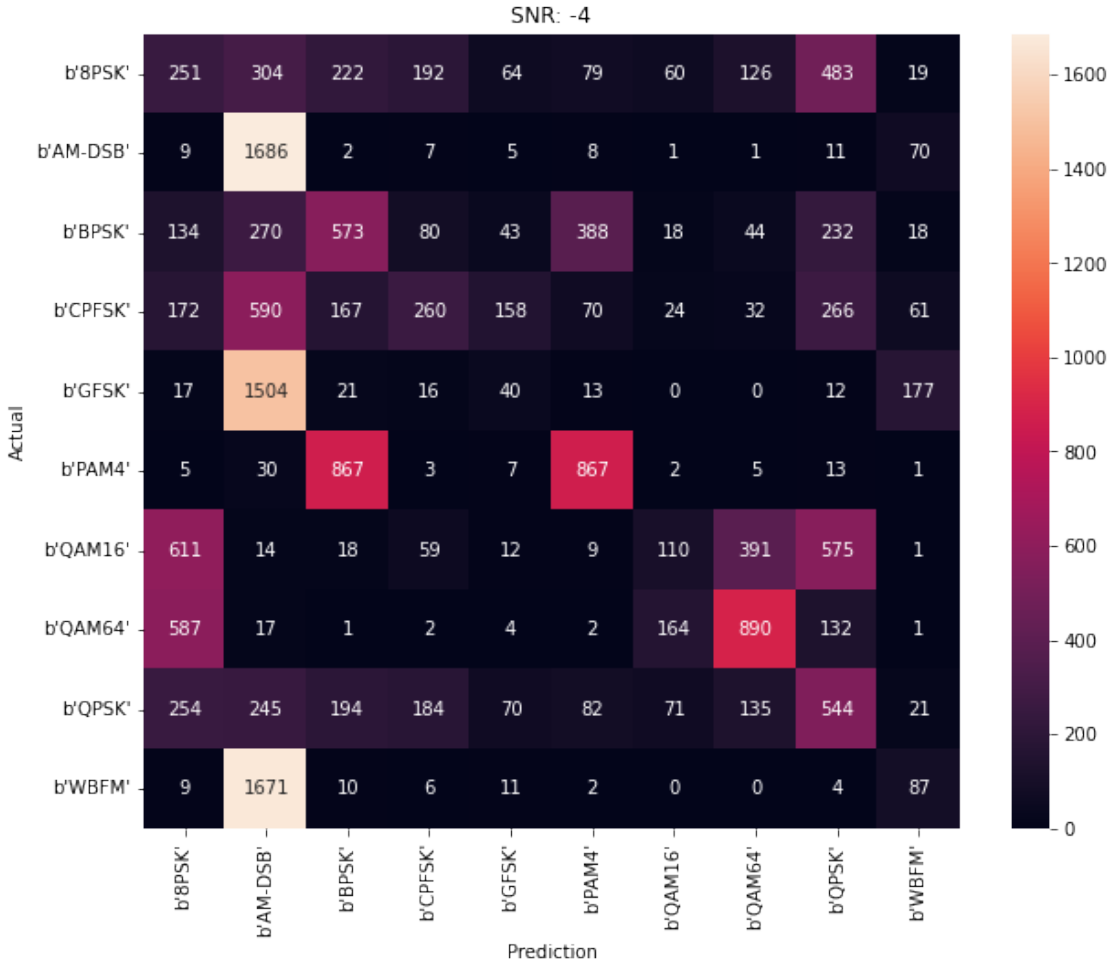

```
Accuracy at SNR = -8 is 0.15516666666666667%
```



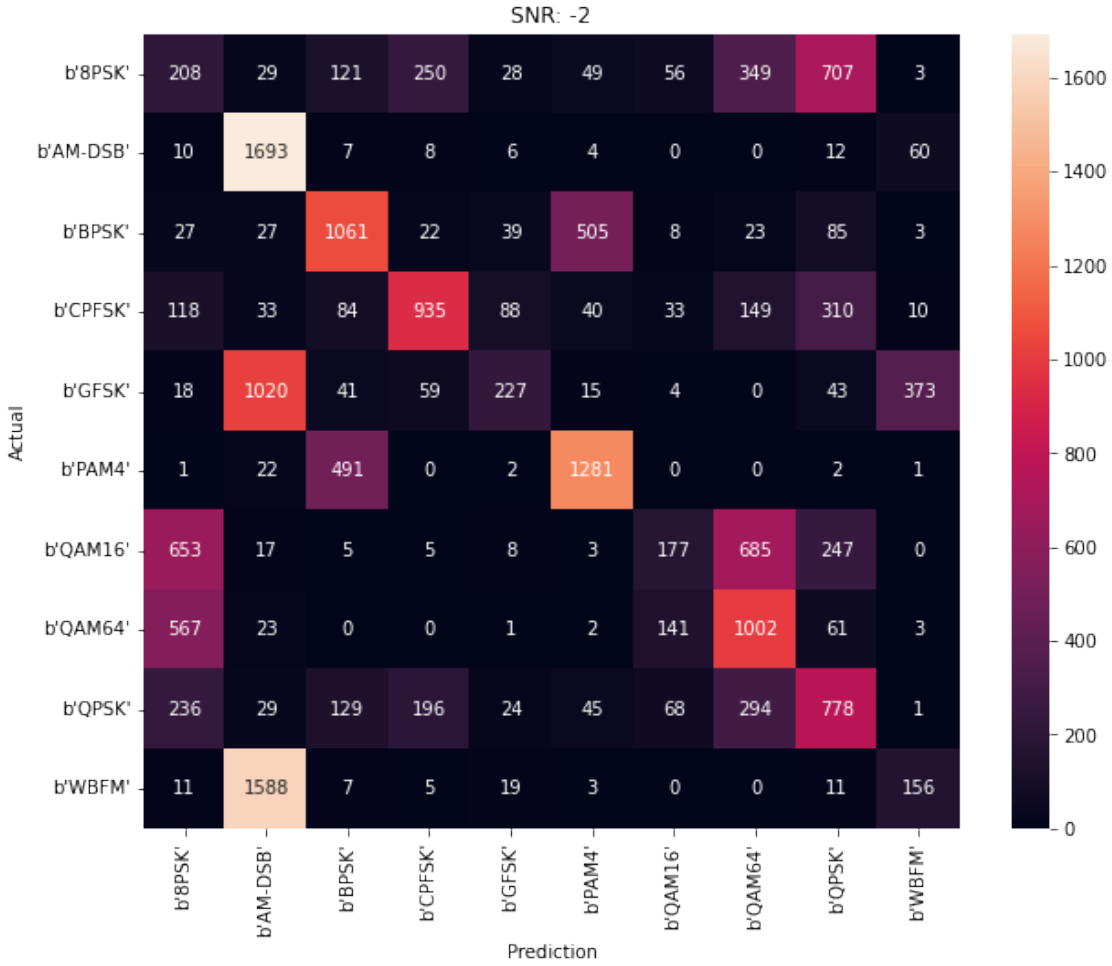
Accuracy at SNR = -6 is 0.20605555555555555%



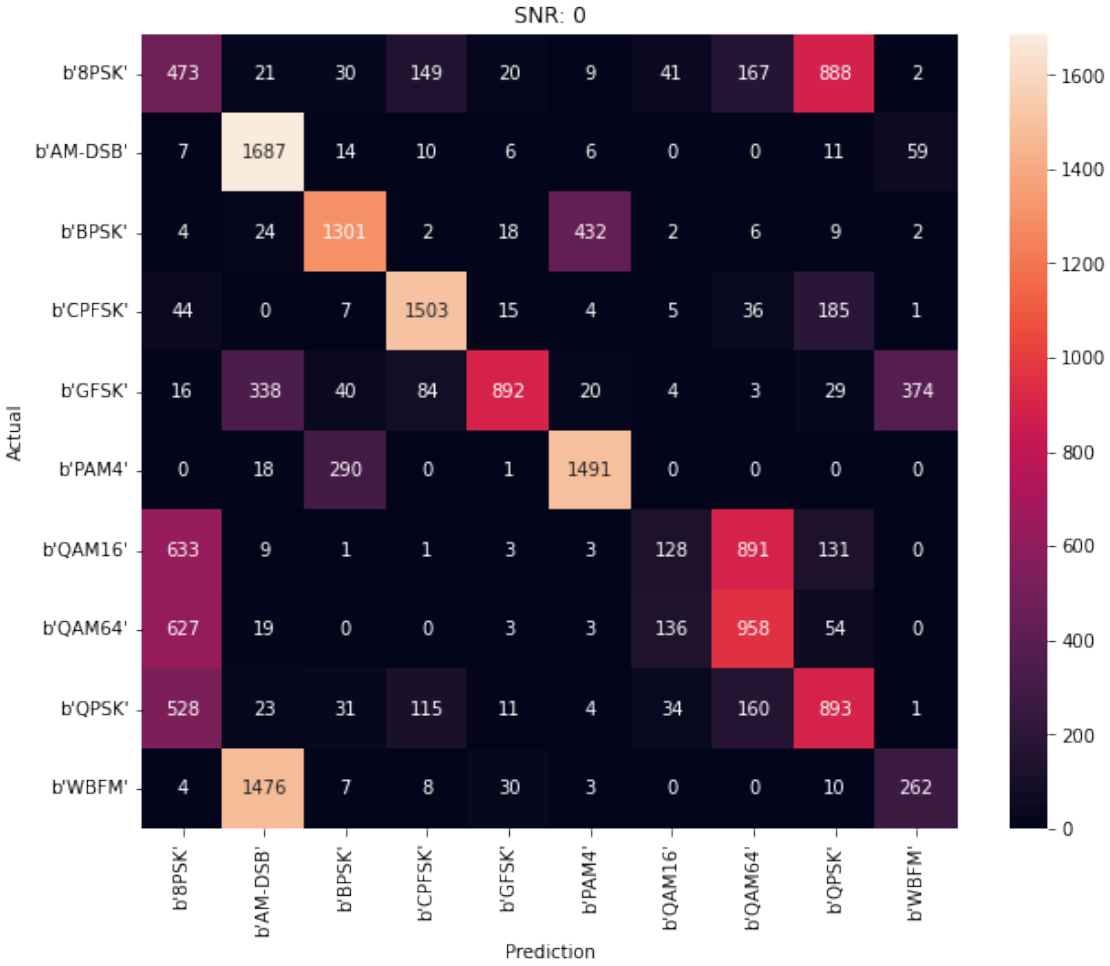

```
Accuracy at SNR = -4 is 0.29488888888888887%
```



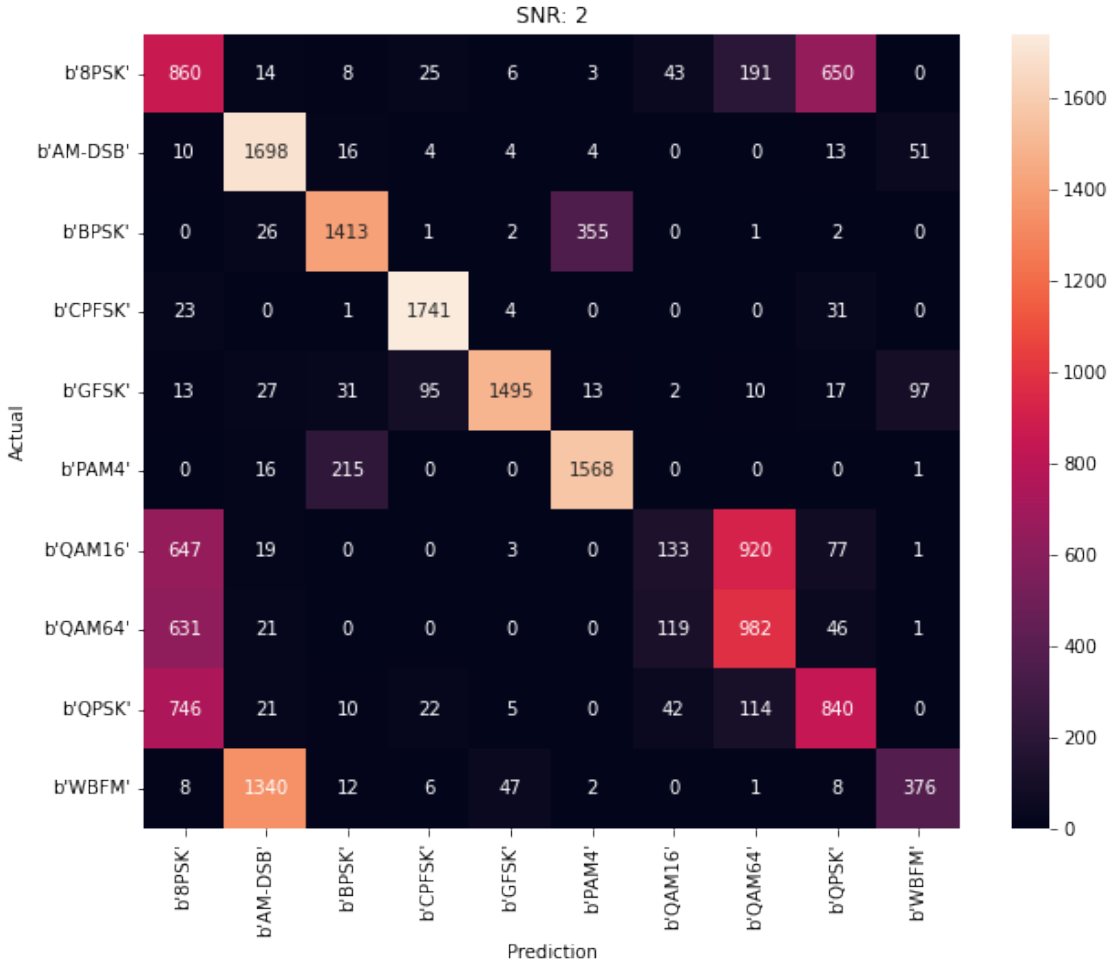

```
Accuracy at SNR = -2 is 0.4176666666666667%
```



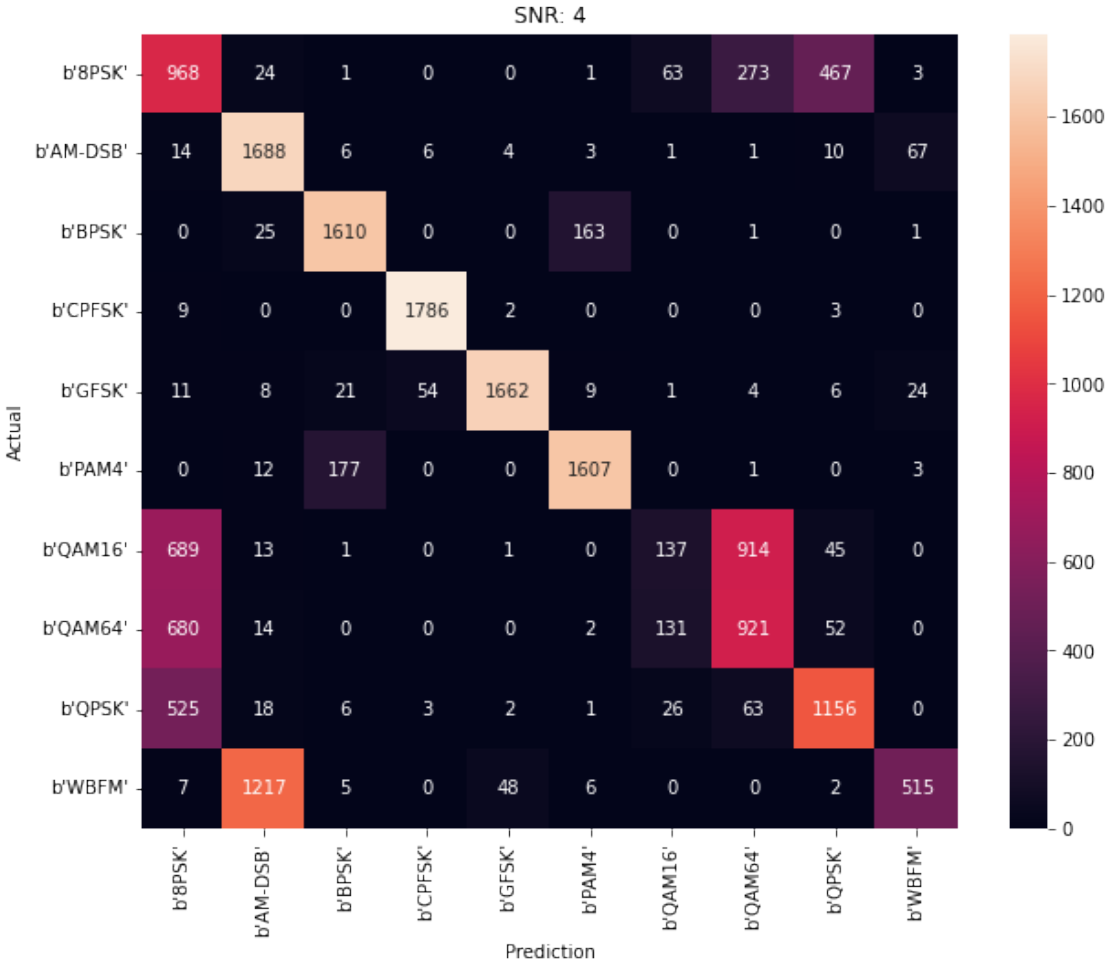

```
Accuracy at SNR = 0 is 0.5326666666666666%
```



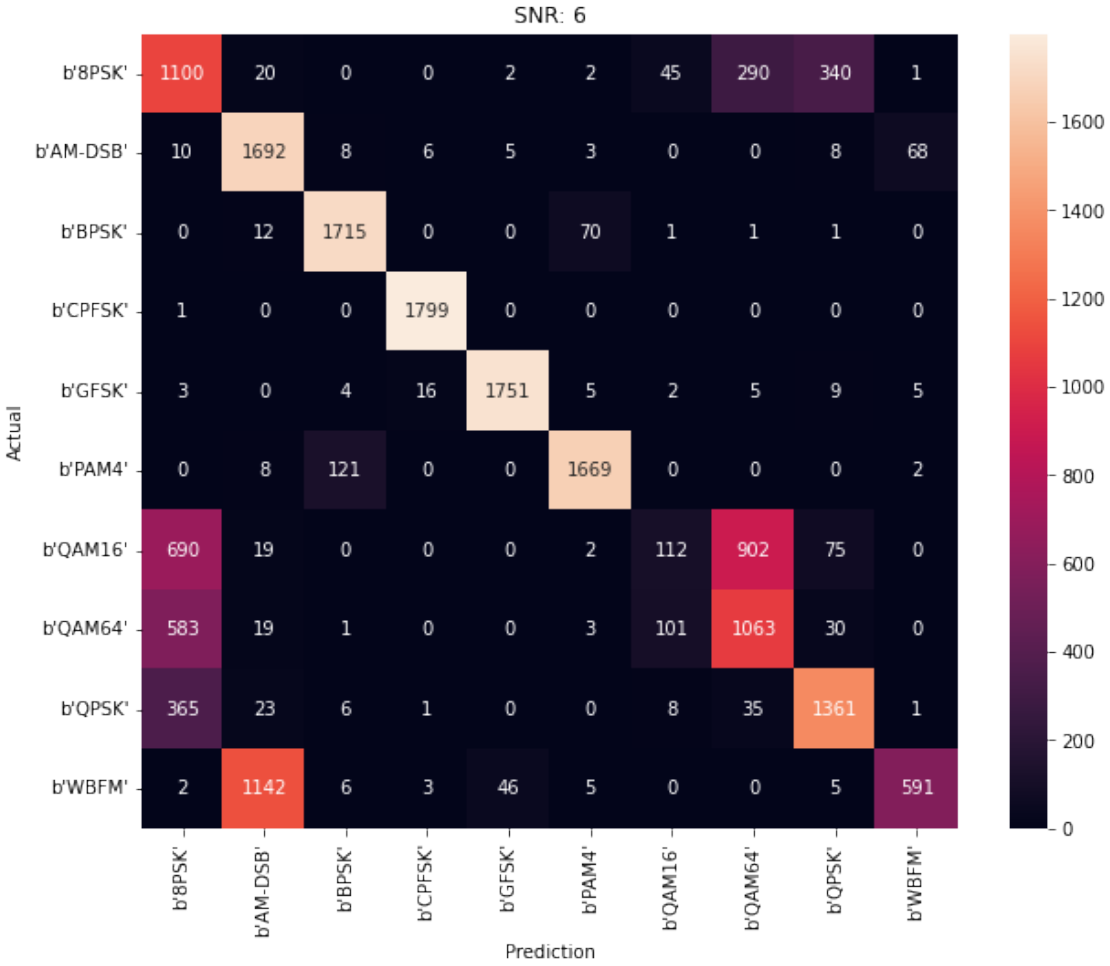

```
Accuracy at SNR = 2 is 0.617%
```



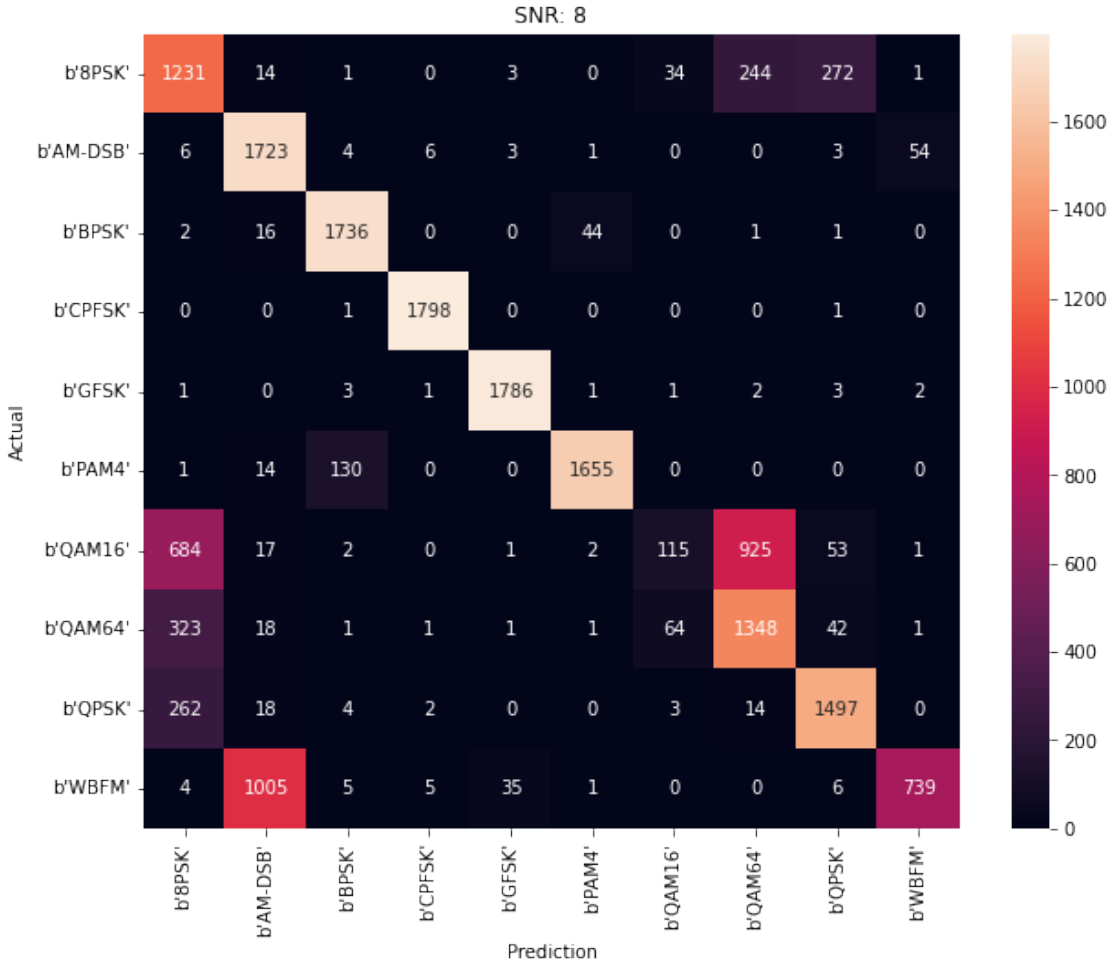
Accuracy at SNR = 4 is 0.6694444444444444%



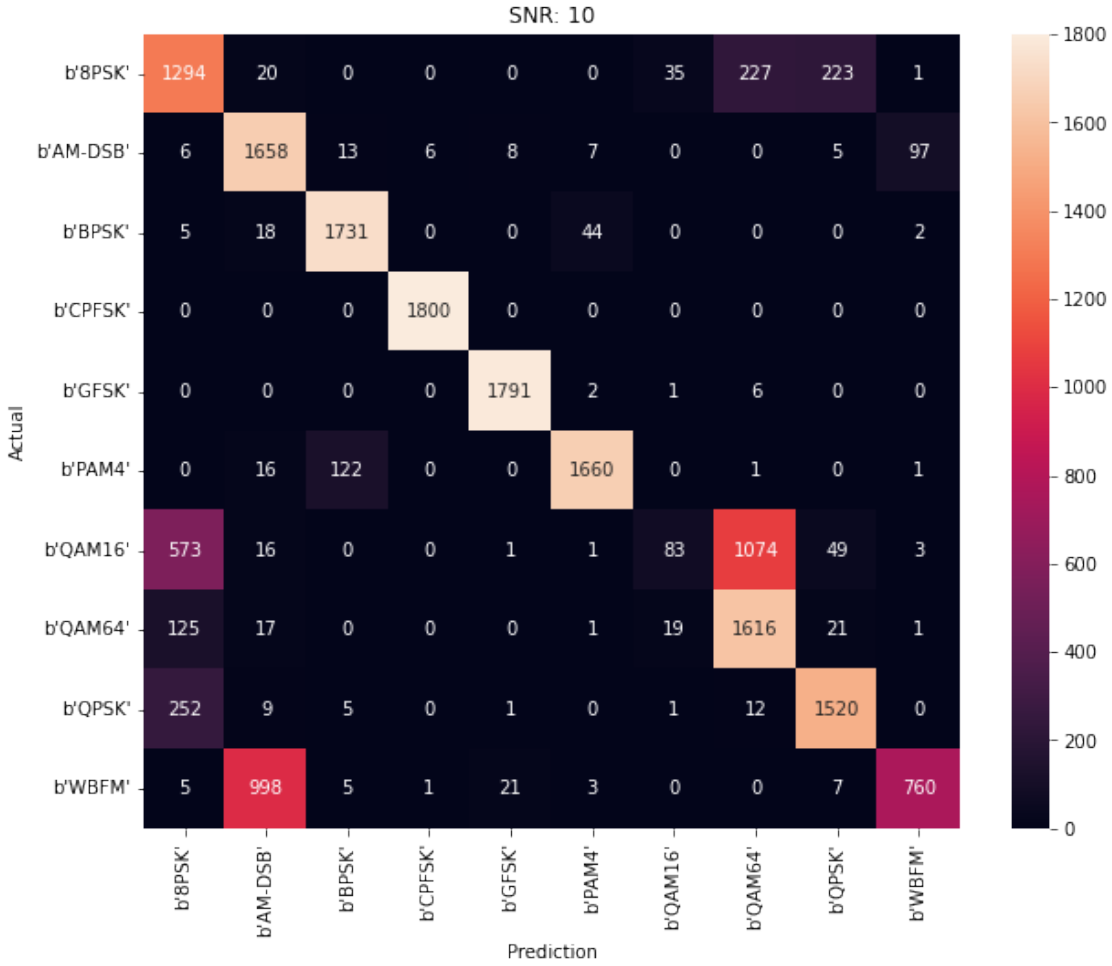

```
Accuracy at SNR = 6 is 0.7140555555555556%
```



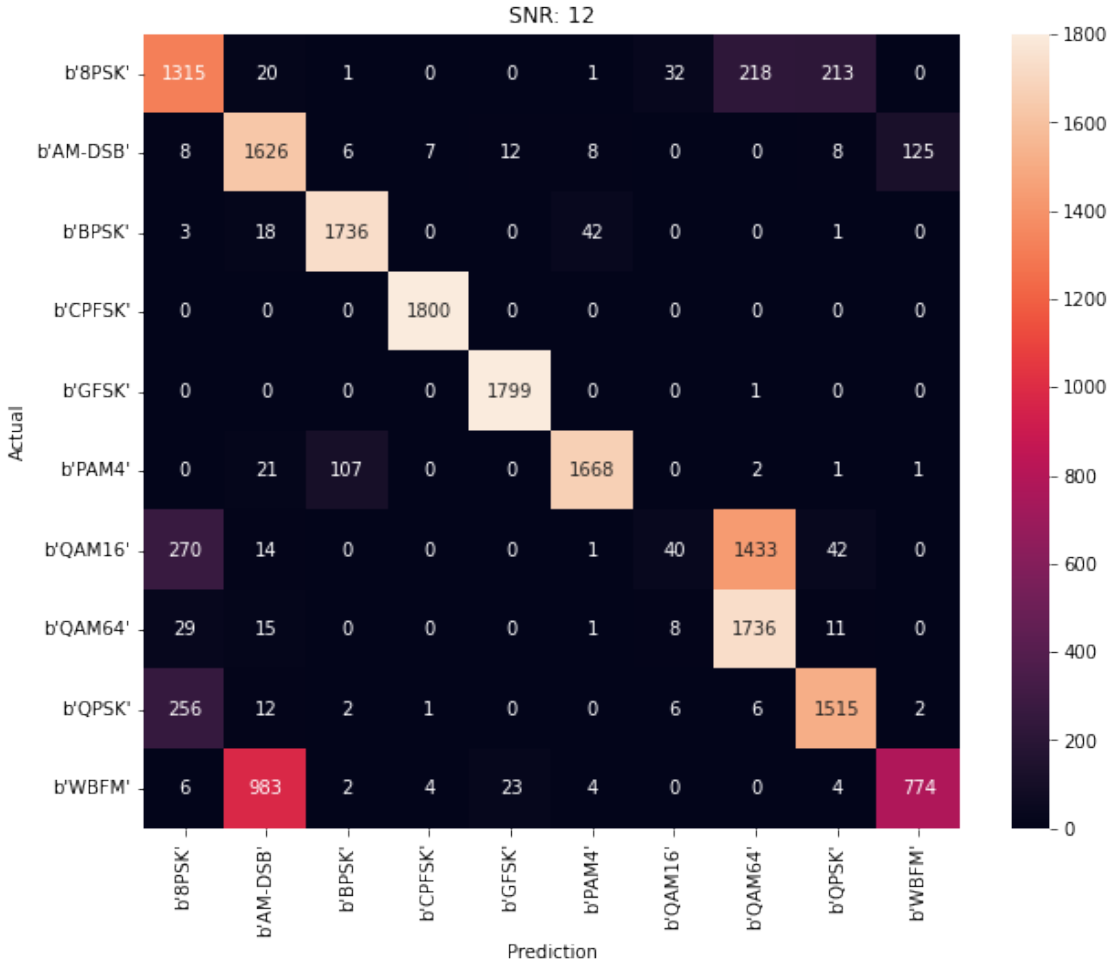
Accuracy at SNR = 8 is 0.7571111111111111%



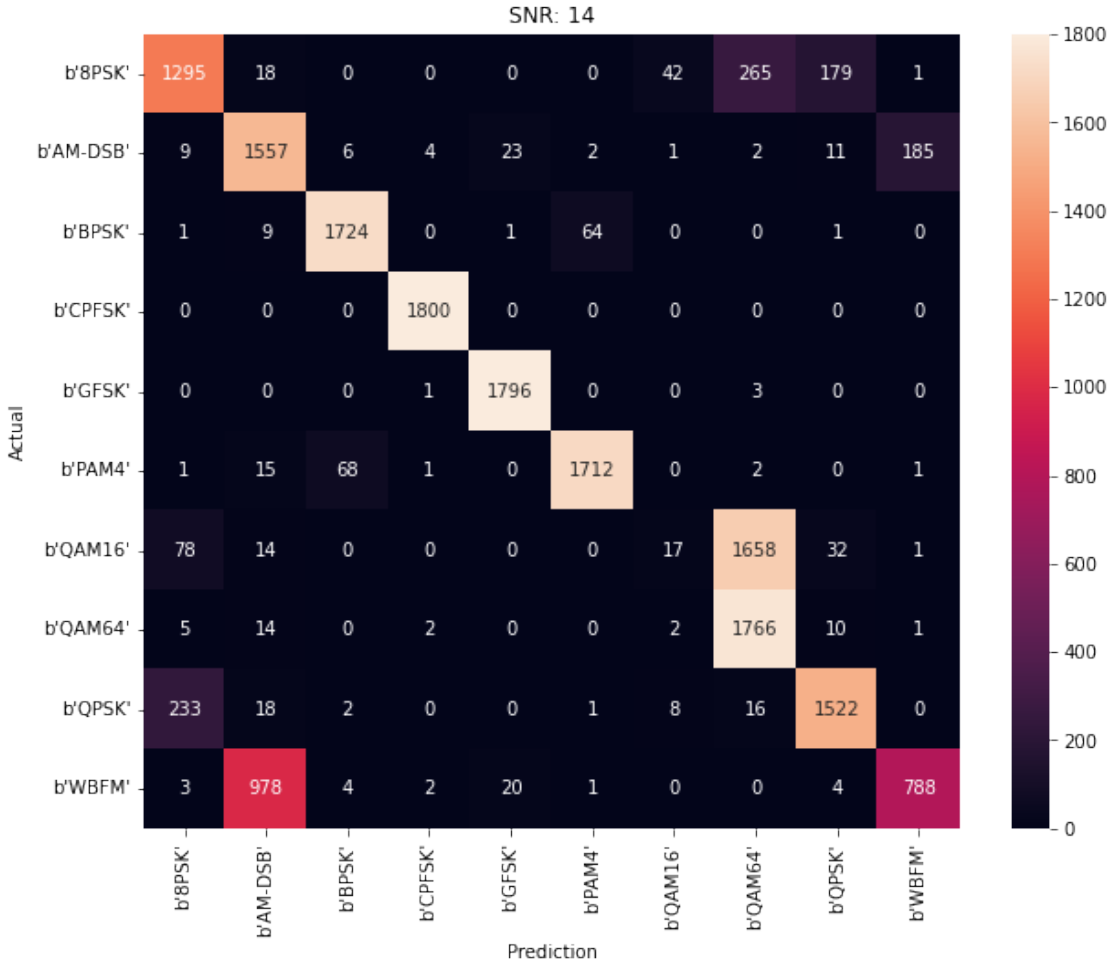
Accuracy at SNR = 10 is 0.7729444444444444%



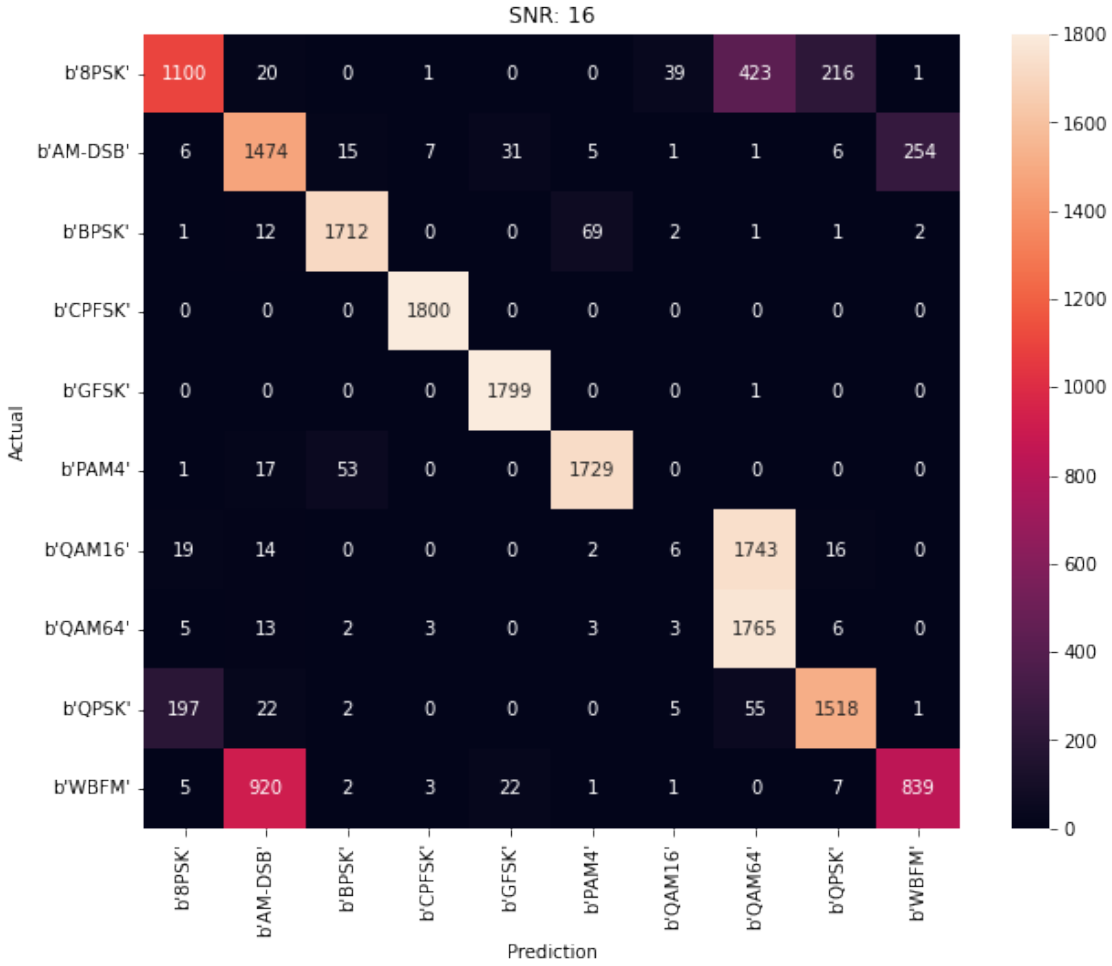
Accuracy at SNR = 12 is 0.7782777777777777%



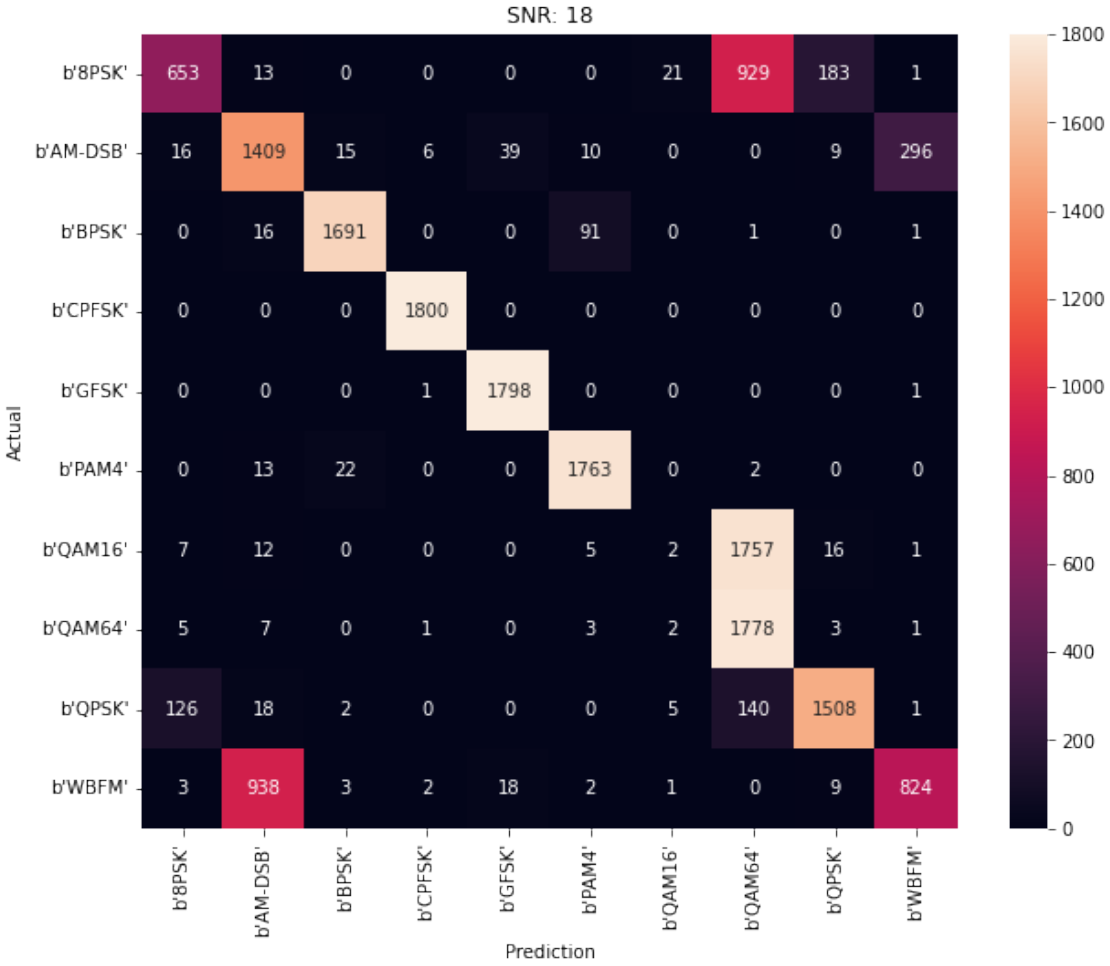
Accuracy at SNR = 14 is 0.7765%

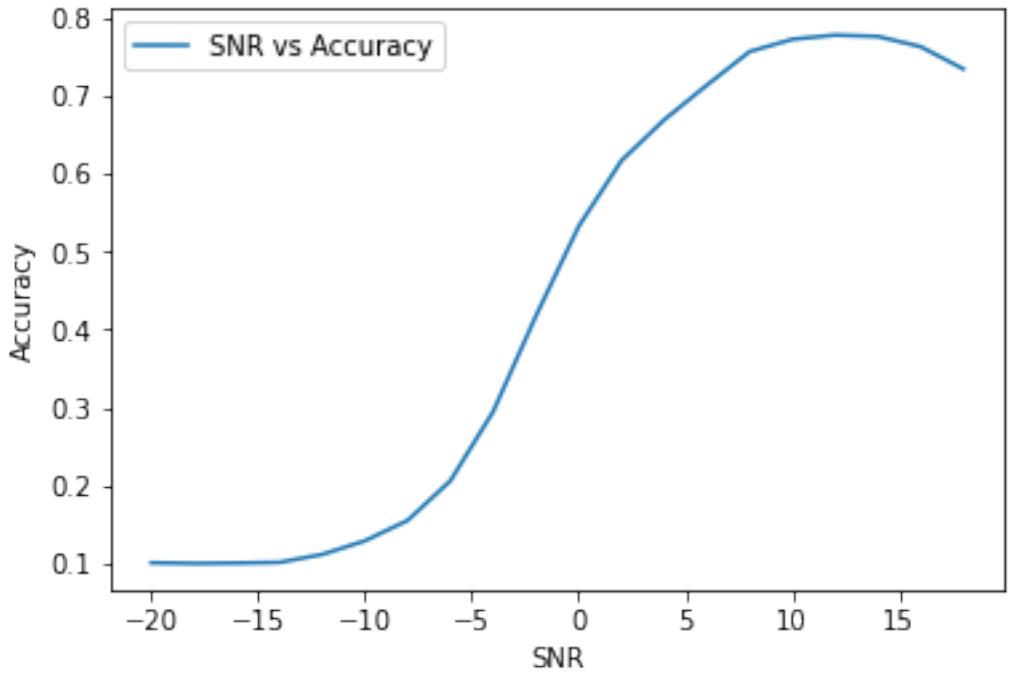



```
Accuracy at SNR = 16 is 0.7634444444444445%
```




```
Accuracy at SNR = 18 is 0.7347777777777778%
```


SNR: 18
b'8PSK' 653 13 0 0 0 0 21 929 183 1
b'AM-DSB' 16 1409 15 6 39 10 0 0 9 296
b'BPSK' 0 16 1691 0 0 91 0 1 0 1
b'CPFSK' 0 0 0 1800 0 0 0 0 0 0
b'GFSK' 0 0 0 1 1798 0 0 0 0 1
b'PAM4' 0 13 22 0 0 1763 0 2 0 0
b'QAM16' 7 12 0 0 0 5 2 1757 16 1
b'QAM64' 5 7 0 1 0 3 2 1778 3 1
b'QPSK' 126 18 2 0 0 0 5 140 1508 1
b'WBFM' 3 938 3 2 18 2 1 0 9 824
Actual
b'8PSK'
b'AM-DSB'
b'BPSK'
b'CPFSK'
b'GFSK'
b'PAM4'
b'QAM16'
b'QAM64'
b'QPSK'
b'WBFM'
Prediction
1800
1600
1400
1200
1000
800
600
400
200
0



7.2 Reshaping data for RNN and LSTM models

[ ]:
```
fdit_training_data, fdit_validation_data, fdit_testing_data =␣
↪reshape_data_for_rnn_lstm(fdit_training_data, fdit_validation_data,␣
↪fdit_testing_data)
```

[ ]:
```
print('training data shape:', fdit_training_data.shape)
print('validation data shape:', fdit_validation_data.shape)
print('testing data shape:', fdit_testing_data.shape)
```

```
training data shape: (798000, 2, 128)
validation data shape: (42000, 2, 128)
testing data shape: (360000, 2, 128)
```

7.3 RNN Model

[ ]:
```
learning_rate = 0.001
batch_size = 512
epochs = 200
```

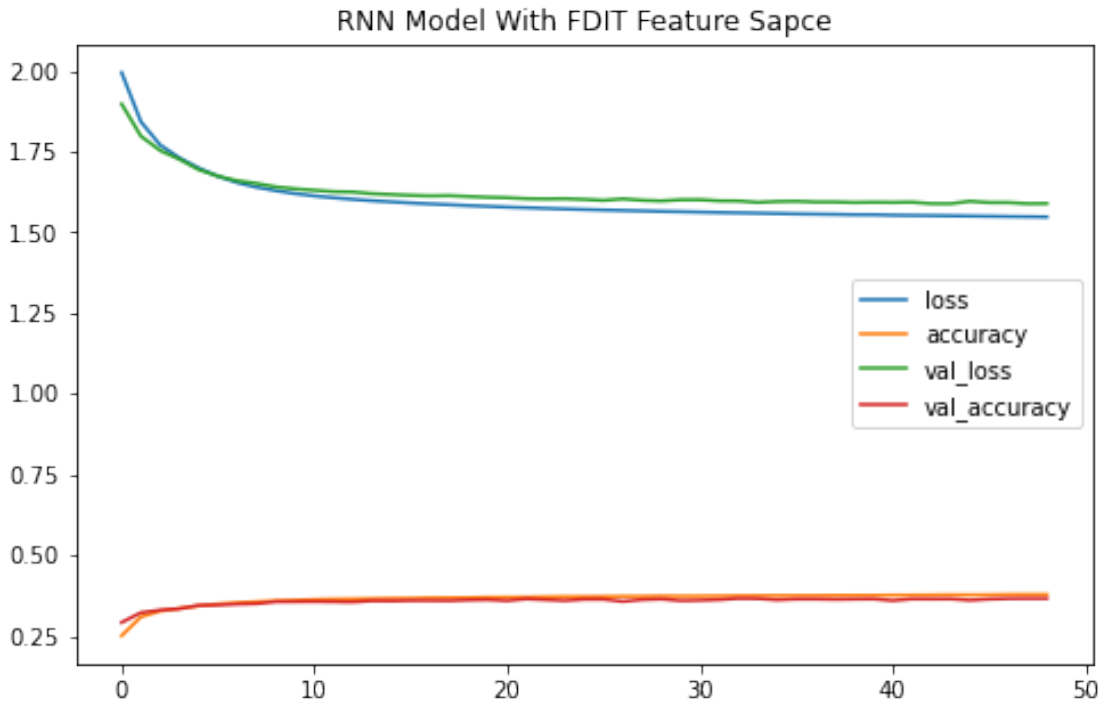
[ ]:
```
rnn_model = Sequential()
rnn_model.add(SimpleRNN(128, activation='relu'))
#rnn_model.add(Dropout(0.5))
rnn_model.add(Dense(10, activation='softmax'))
```

```
rnn_model.compile(loss=tf.keras.losses.CategoricalCrossentropy(),␣
 ↪metrics='accuracy', optimizer=tf.keras.optimizers.
 ↪Adam(learning_rate=learning_rate))
```

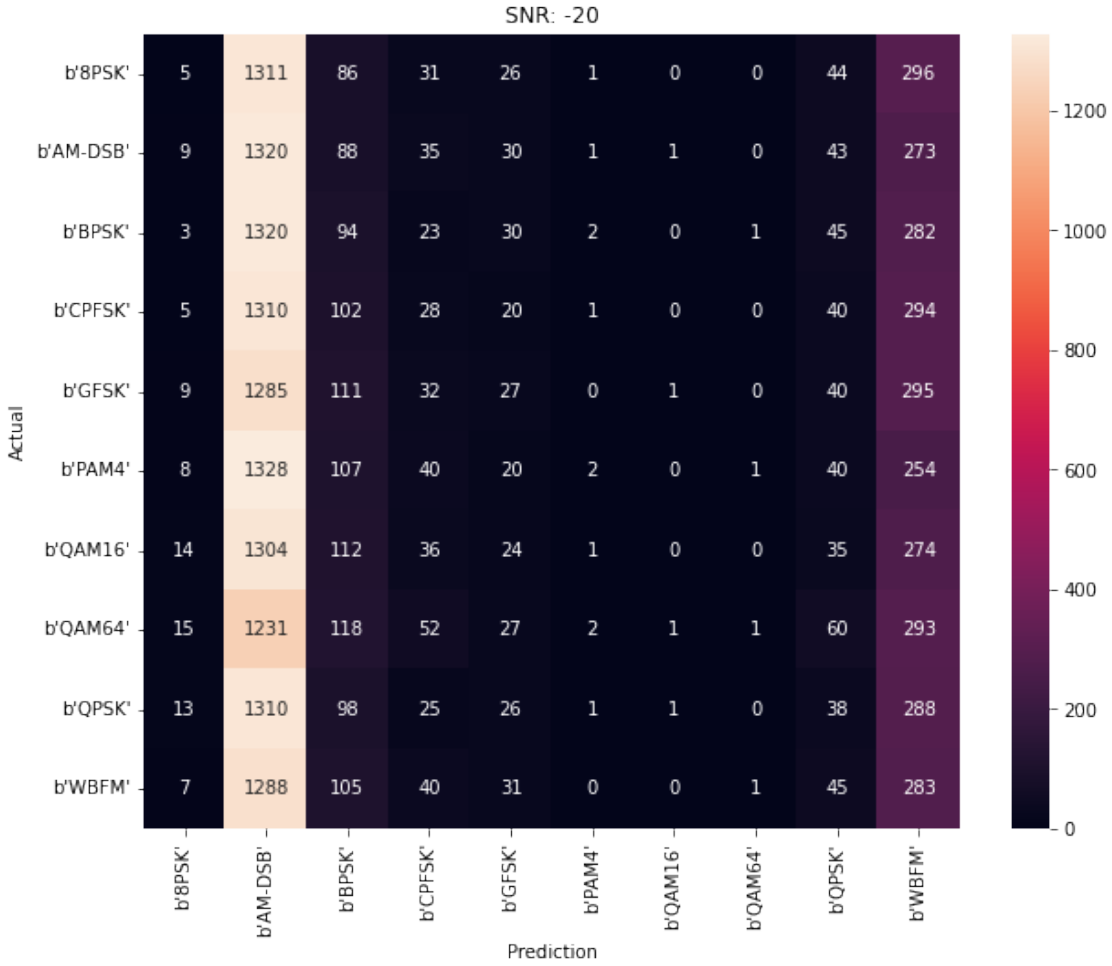
[ ]:
```
es = tf.keras.callbacks.EarlyStopping(monitor="val_loss", patience=5,␣
 ↪restore_best_weights=True,)
checkpointer = ModelCheckpoint(filepath='saved_models/rnn_fdit_classification.
 ↪hdf5', verbose=1, save_best_only=True)

with tf.device('/device:GPU:0'):
  history = rnn_model.fit(fdit_training_data, training_onehot,␣
 ↪batch_size=batch_size, epochs=epochs, validation_data=(fdit_validation_data,␣
 ↪validation_onehot), callbacks=[es, checkpointer], verbose=1)
```

```
Epoch 1/200
1559/1559 [==============================] - ETA: 0s - loss: 1.9940 - accuracy:
0.2511
Epoch 1: val_loss improved from inf to 1.89675, saving model to
saved_models/rnn_fdit_classification.hdf5
1559/1559 [==============================] - 9s 5ms/step - loss: 1.9940 -
accuracy: 0.2511 - val_loss: 1.8967 - val_accuracy: 0.2921

Epoch 49: val_loss did not improve from 1.58818
1559/1559 [==============================] - 8s 5ms/step - loss: 1.5472 -
accuracy: 0.3784 - val_loss: 1.5886 - val_accuracy: 0.3665
```

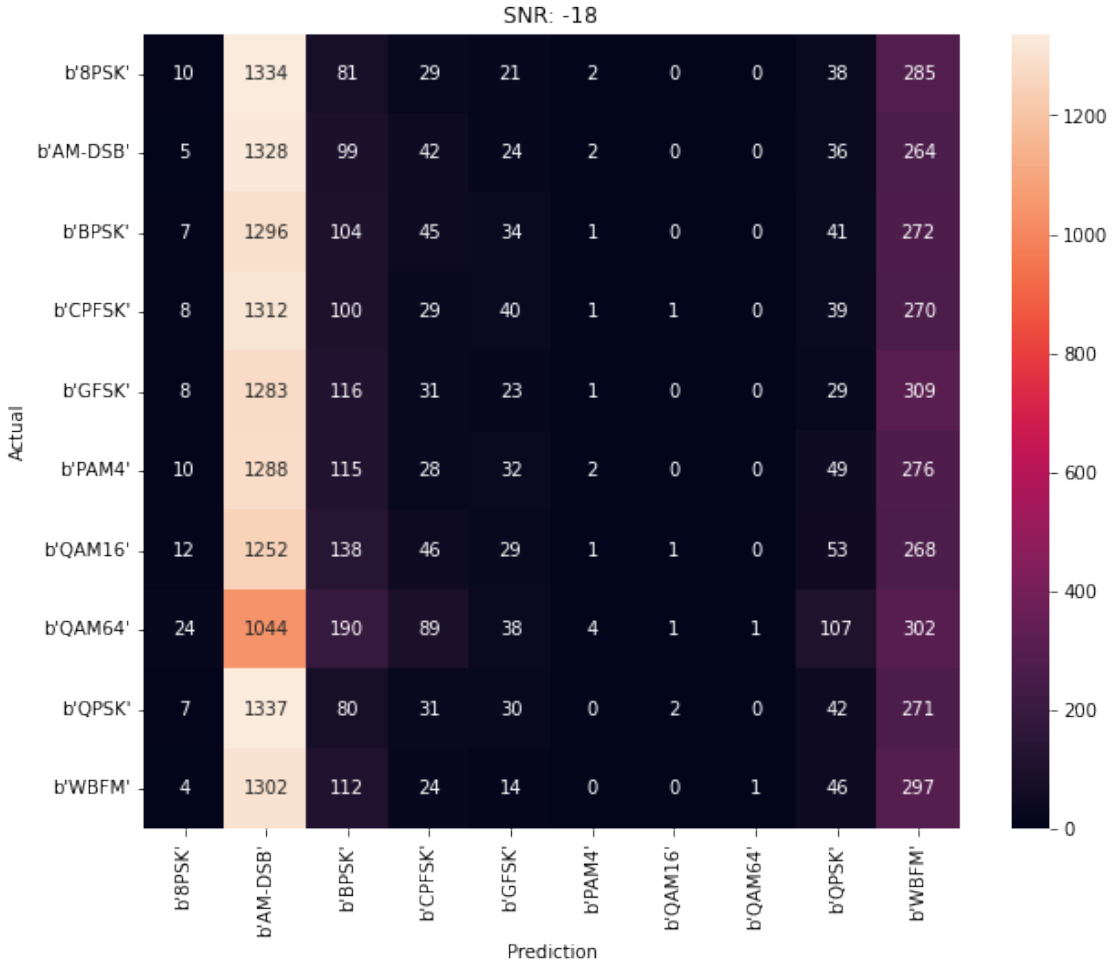
[ ]:
```
plot_model_history(history, 'RNN Model With FDIT Feature Sapce')
model_scoring(rnn_model, history, fdit_testing_data, testing_pair_labels)
```



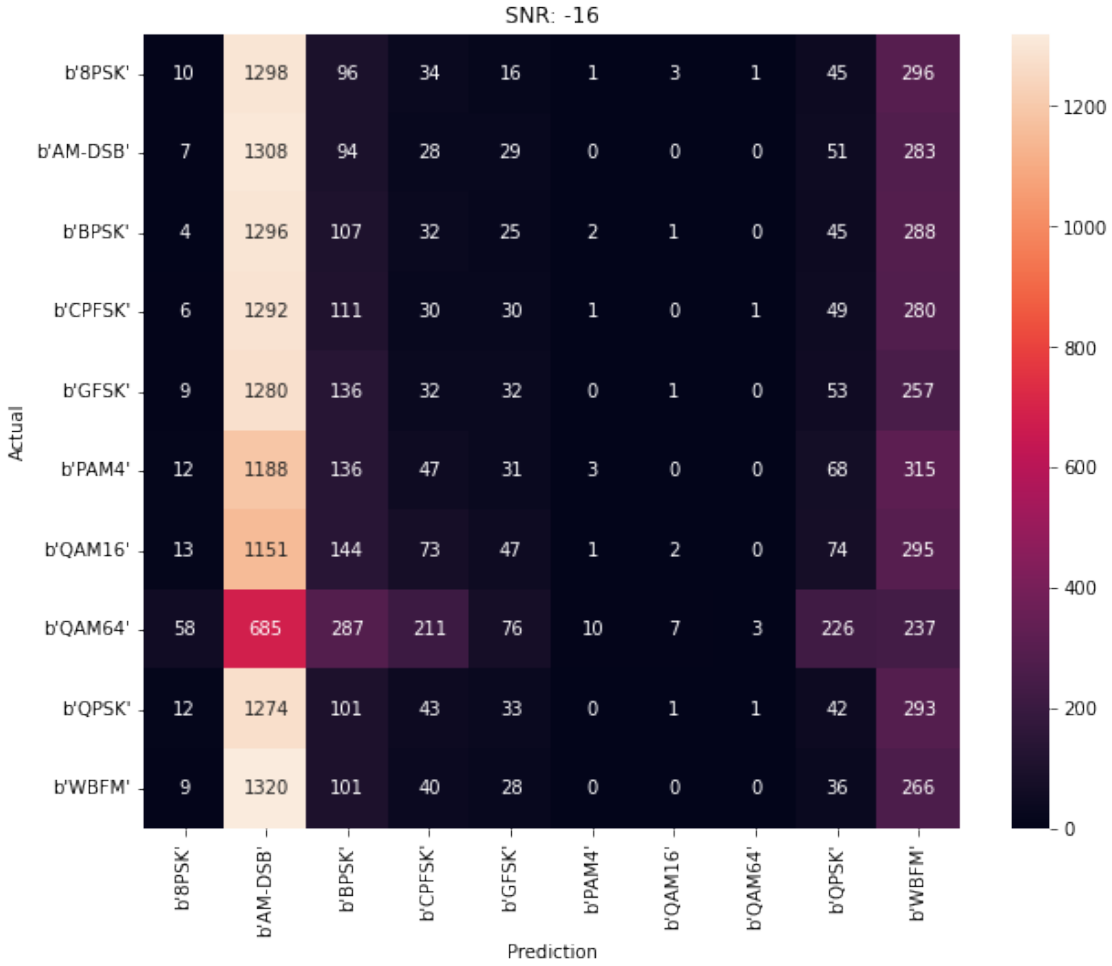

```
Accuracy at SNR = -20 is 0.09988888888888889%
```



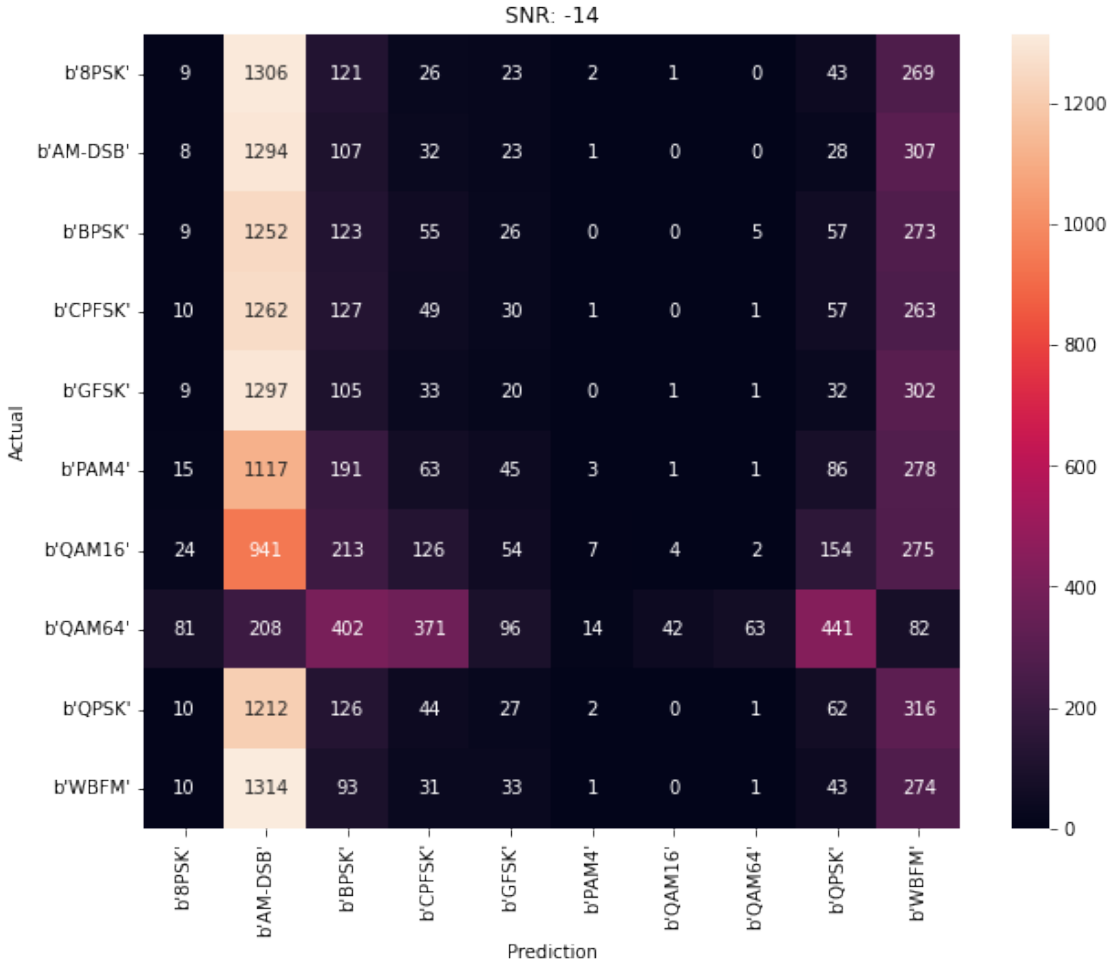

```
Accuracy at SNR = -18 is 0.10205555555555555%
```



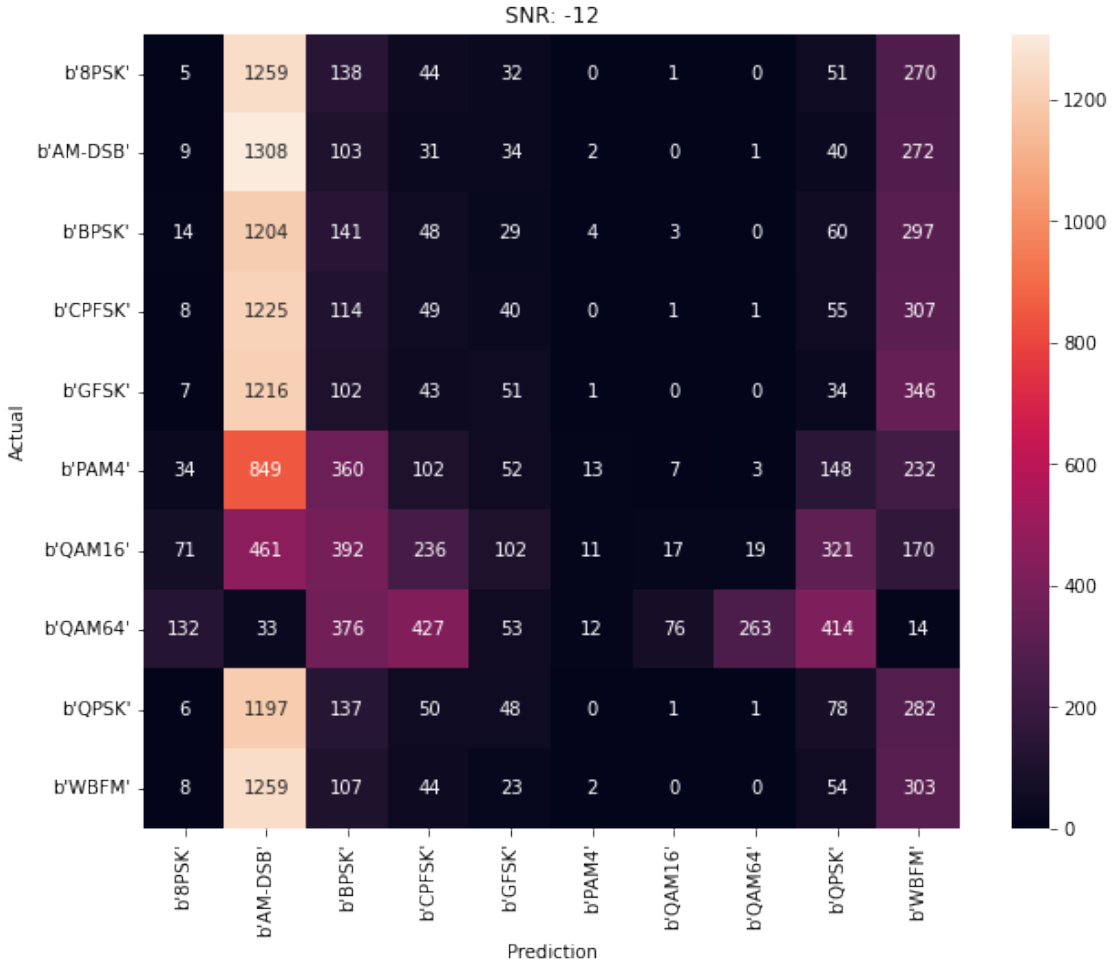

```
Accuracy at SNR = -16 is 0.10016666666666667%
```



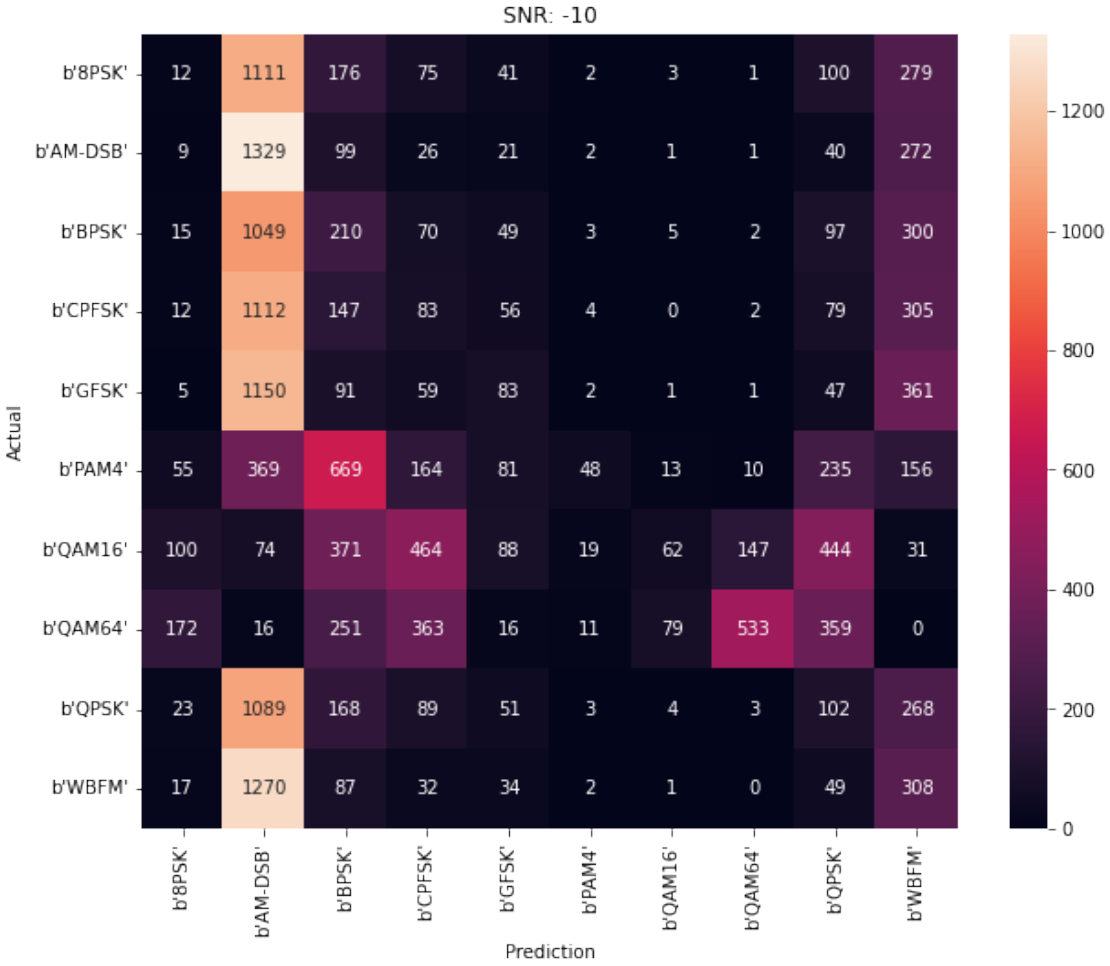
Accuracy at SNR = -14 is 0.10561111111111111%



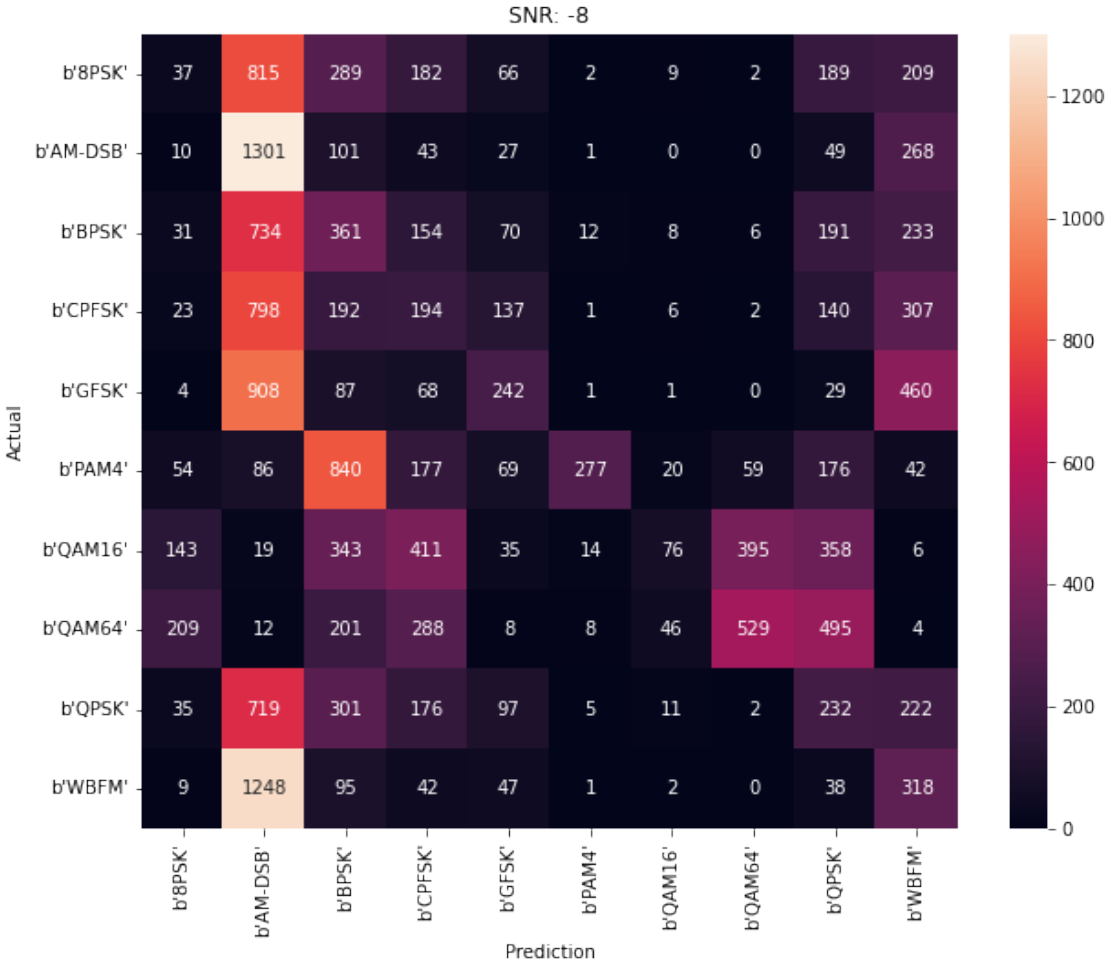

```
Accuracy at SNR = -12 is 0.12377777777777778%
```



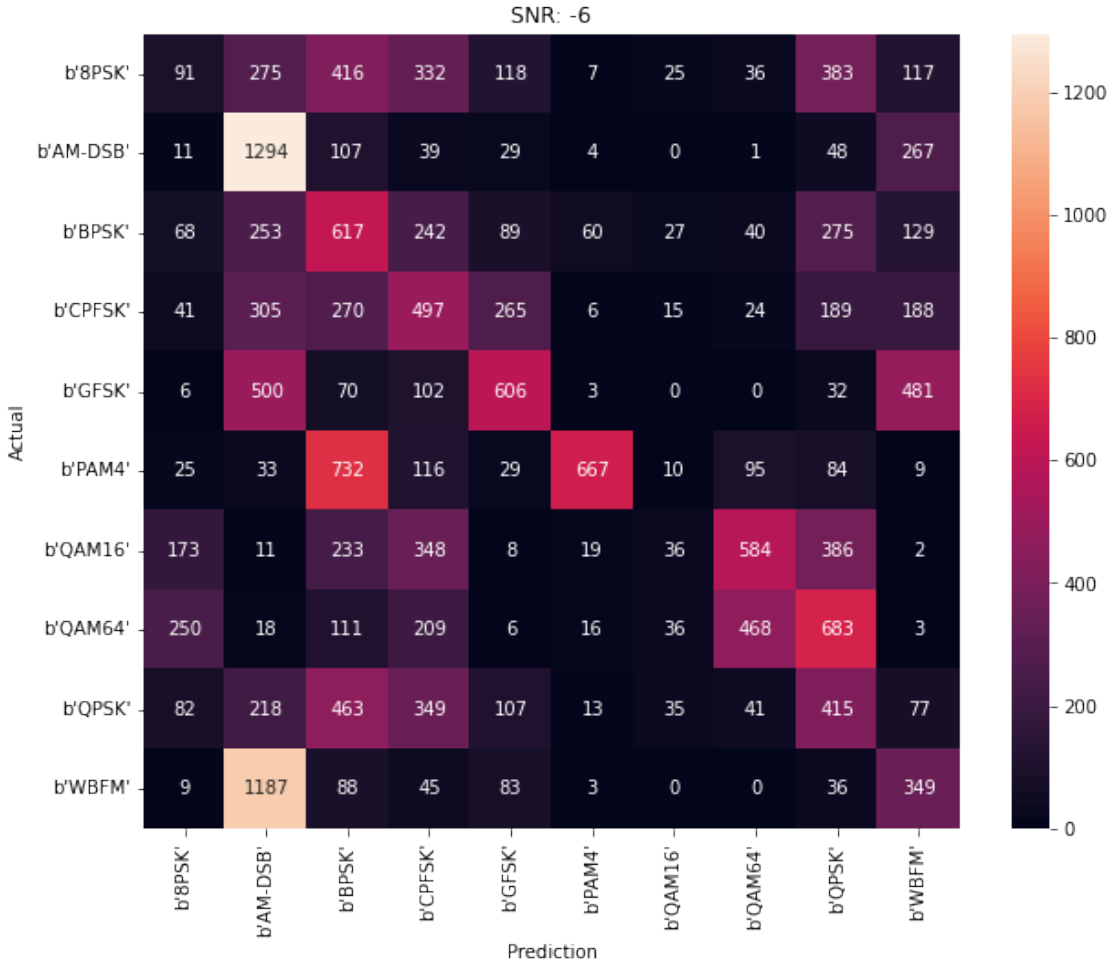

```
Accuracy at SNR = -10 is 0.15388888888888888%
```



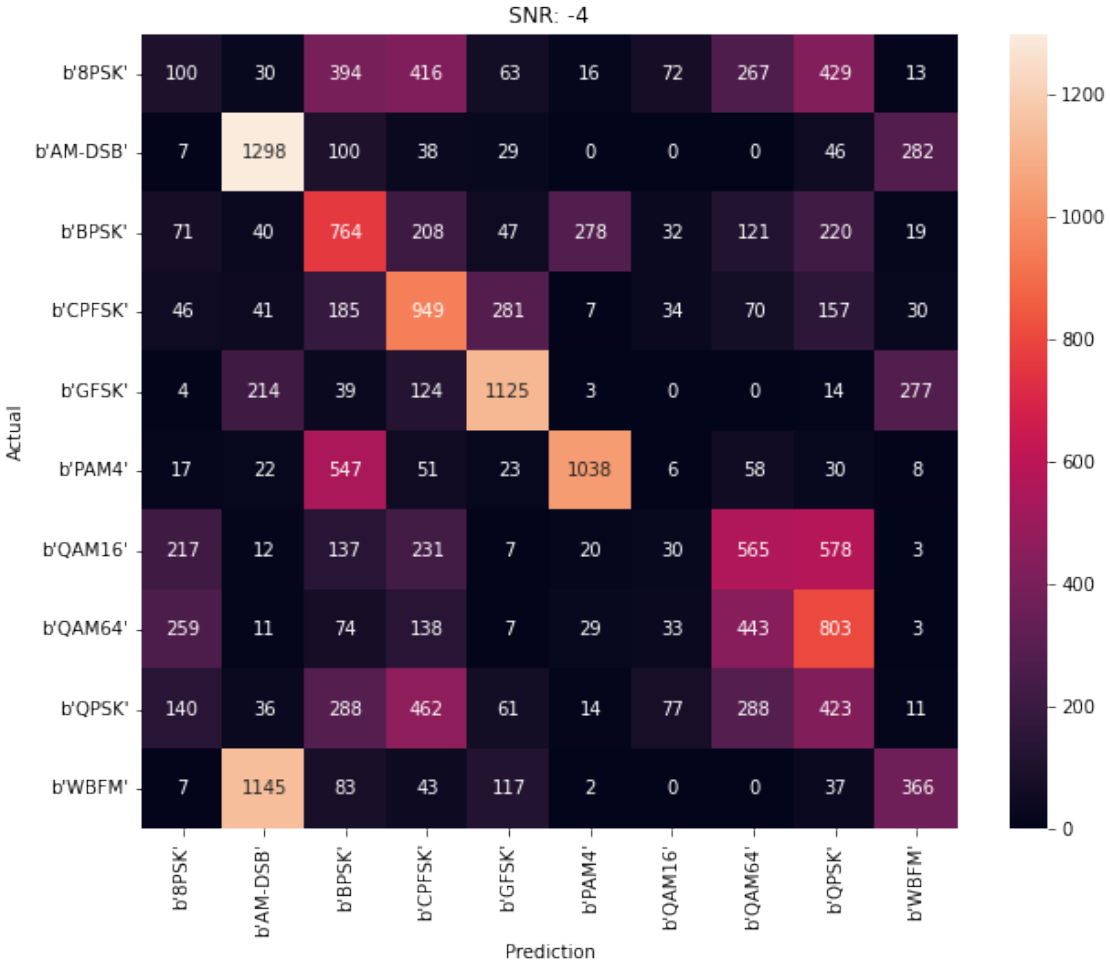

```
Accuracy at SNR = -8 is 0.19816666666666666%
```



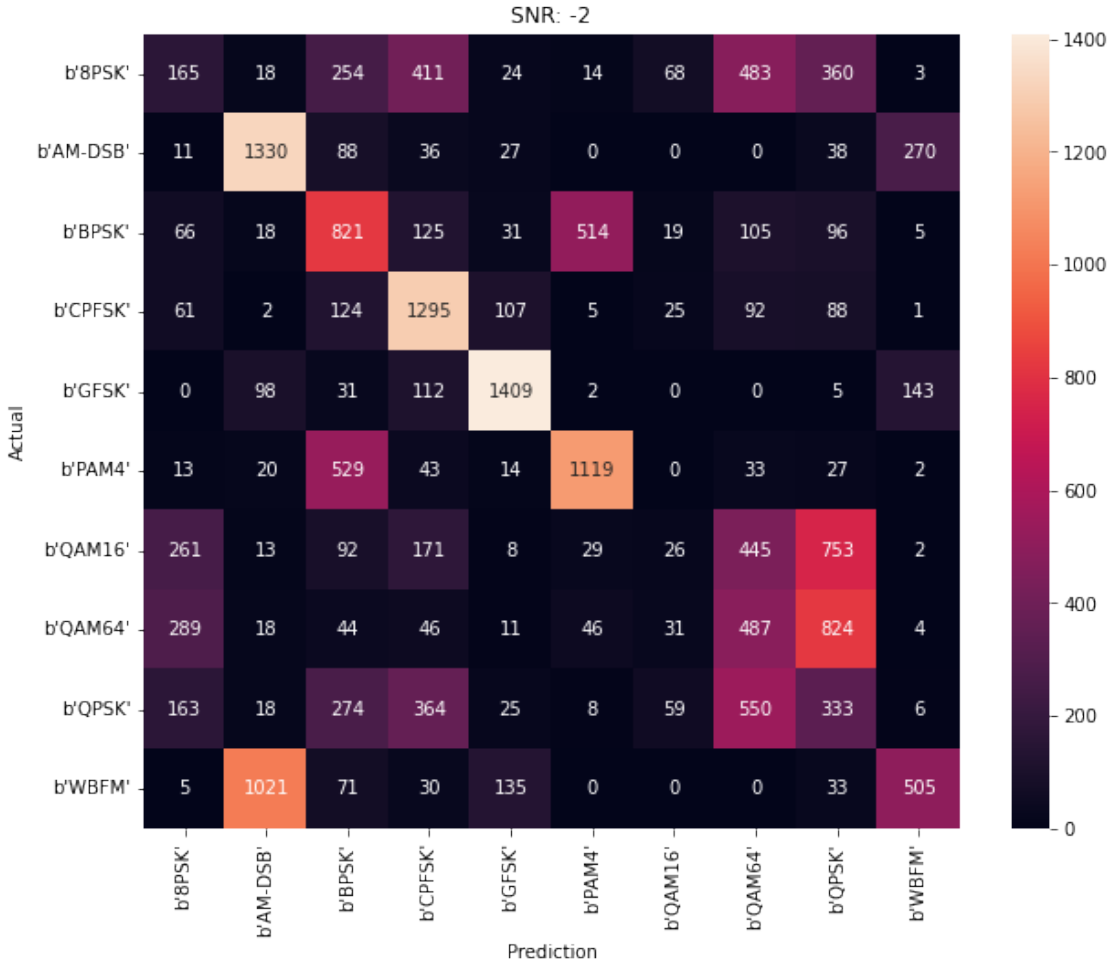

```
Accuracy at SNR = -6 is 0.28%
```



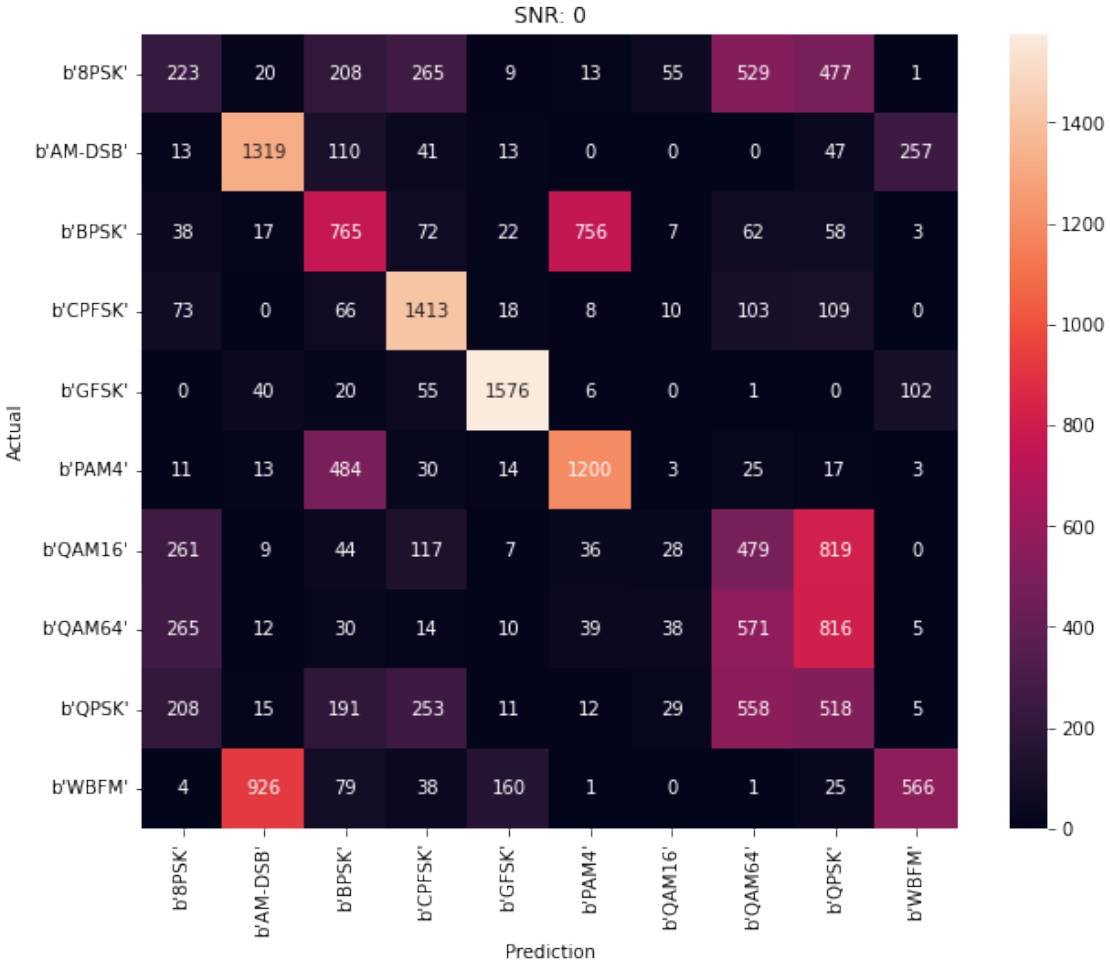

```
Accuracy at SNR = -4 is 0.3631111111111111%
```



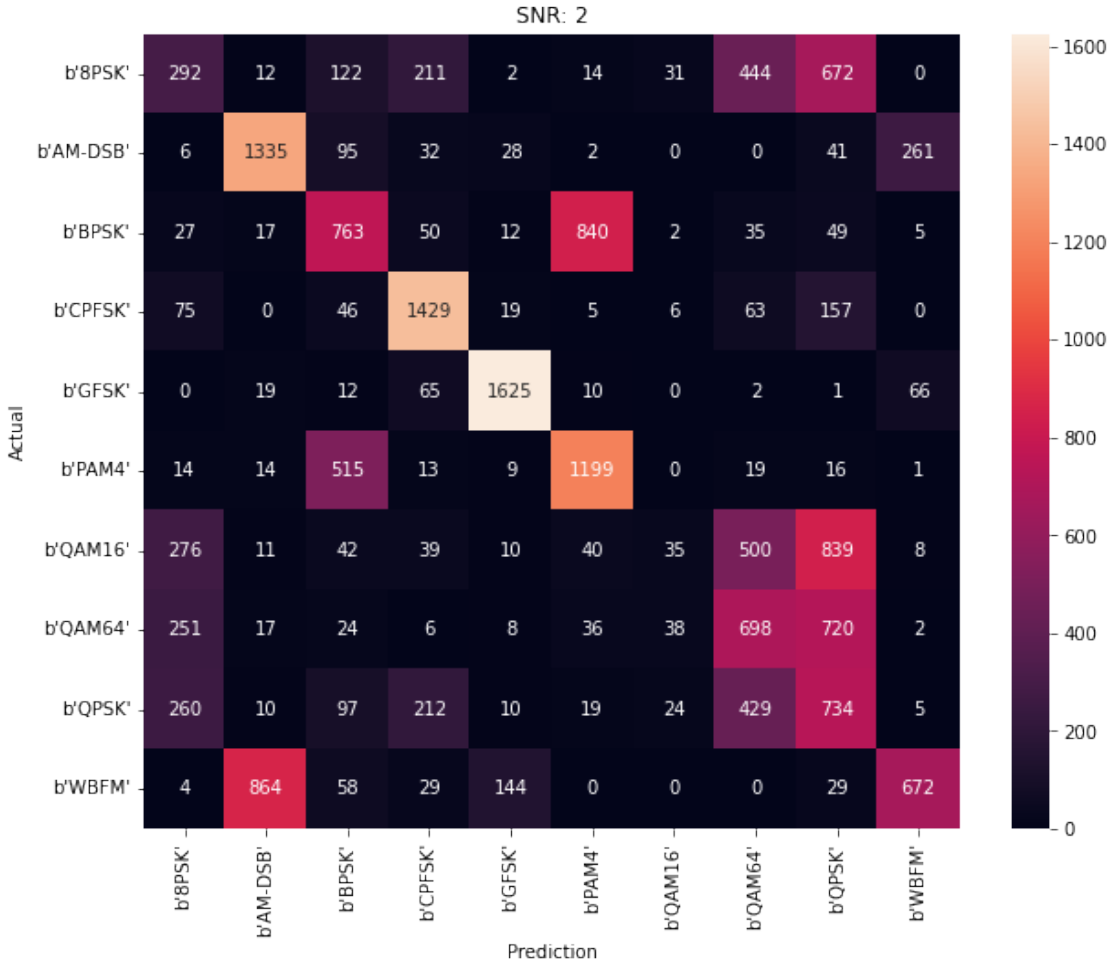

```
Accuracy at SNR = -2 is 0.4161111111111111%
```



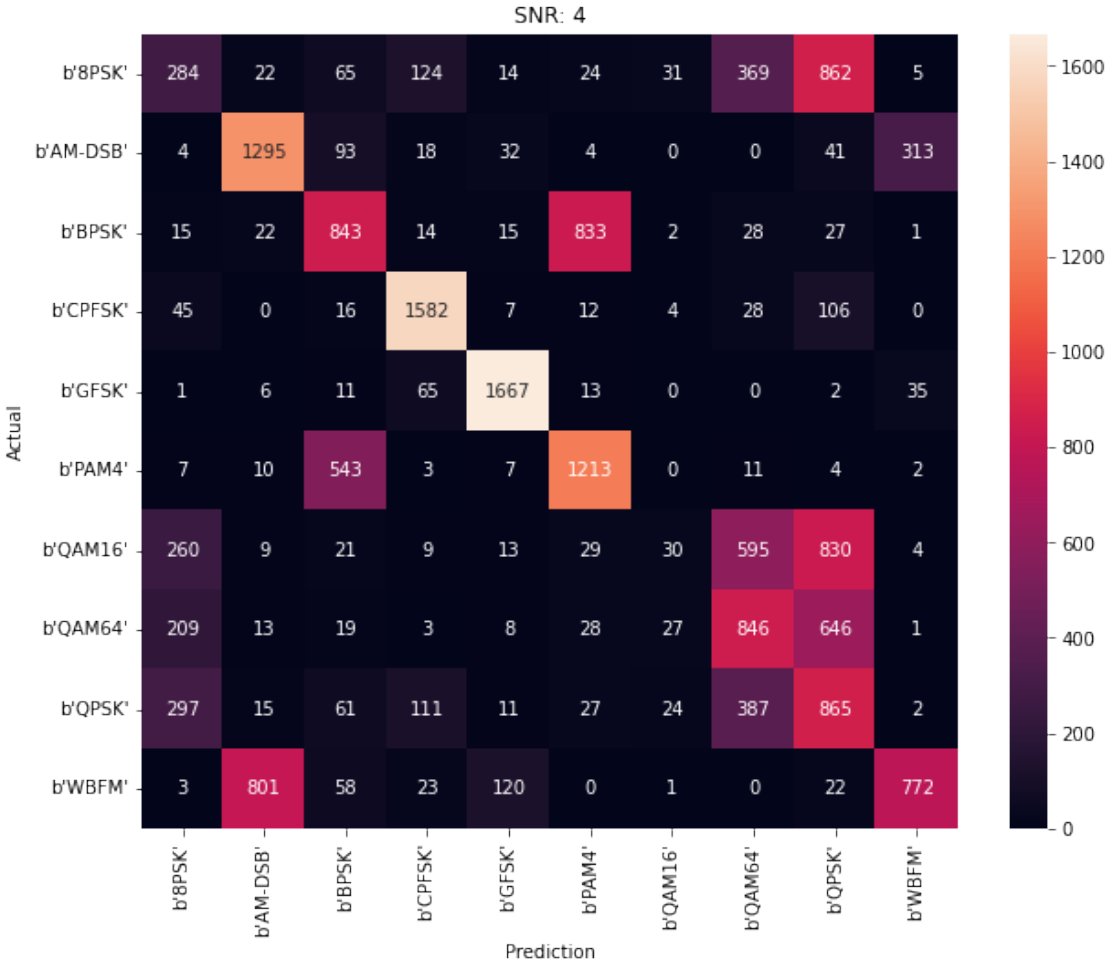

```
Accuracy at SNR = 0 is 0.4543888888888889%
```



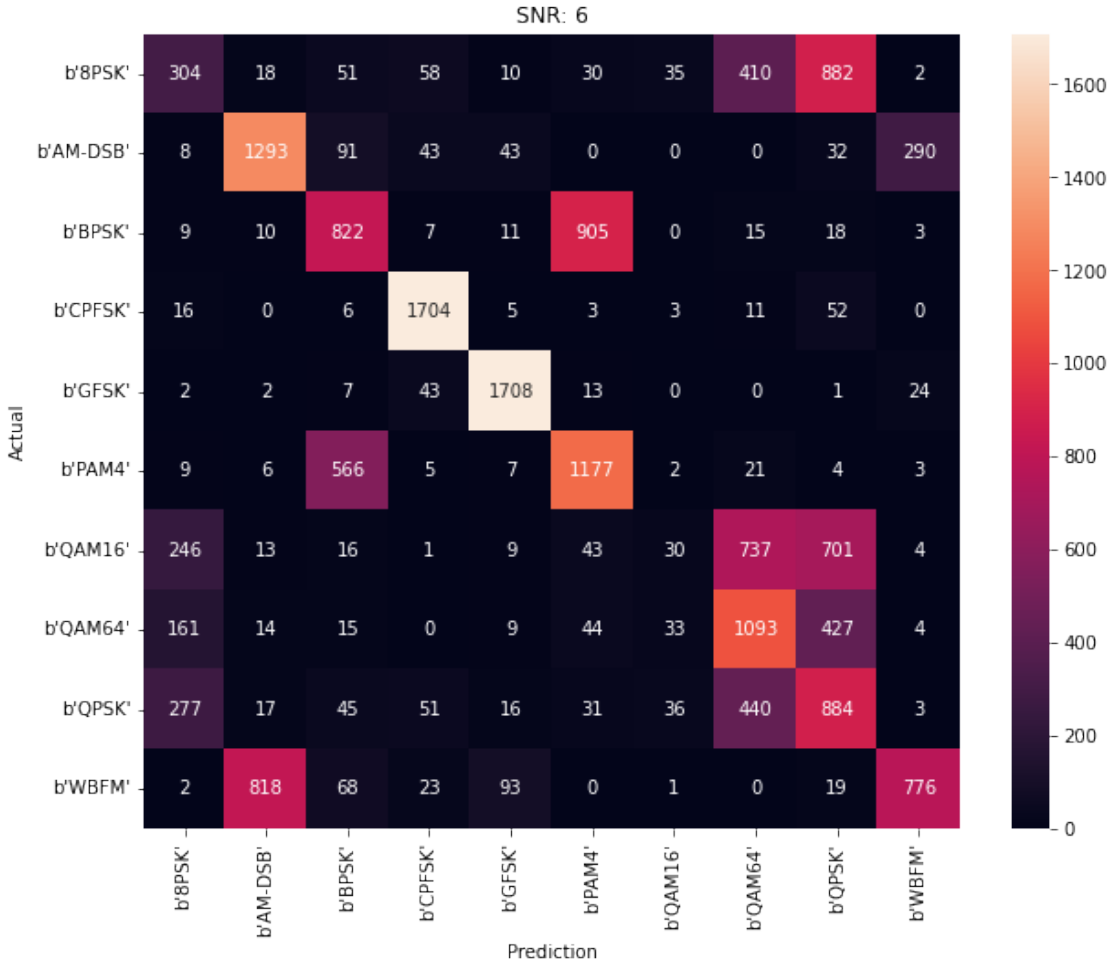

```
Accuracy at SNR = 2 is 0.48788888888888887%
```



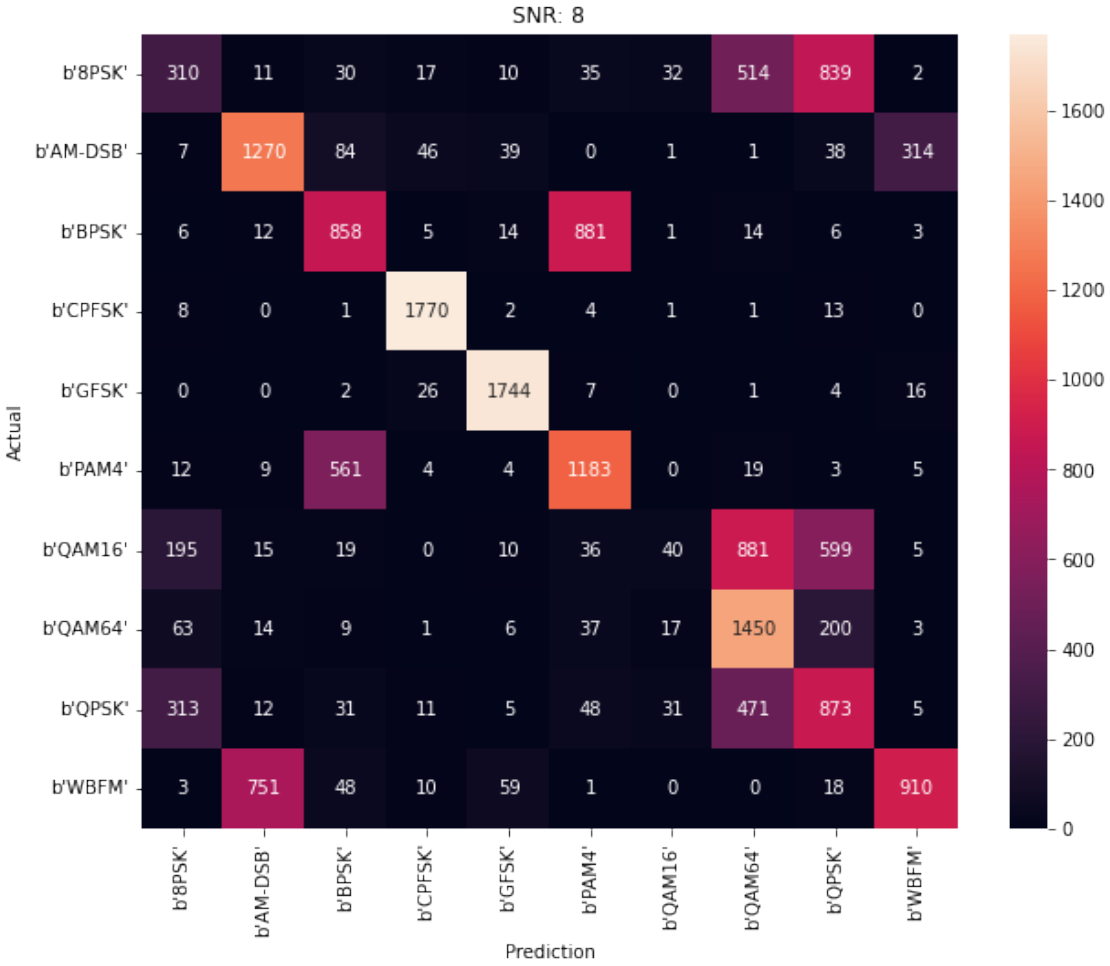

```
Accuracy at SNR = 4 is 0.5220555555555556%
```



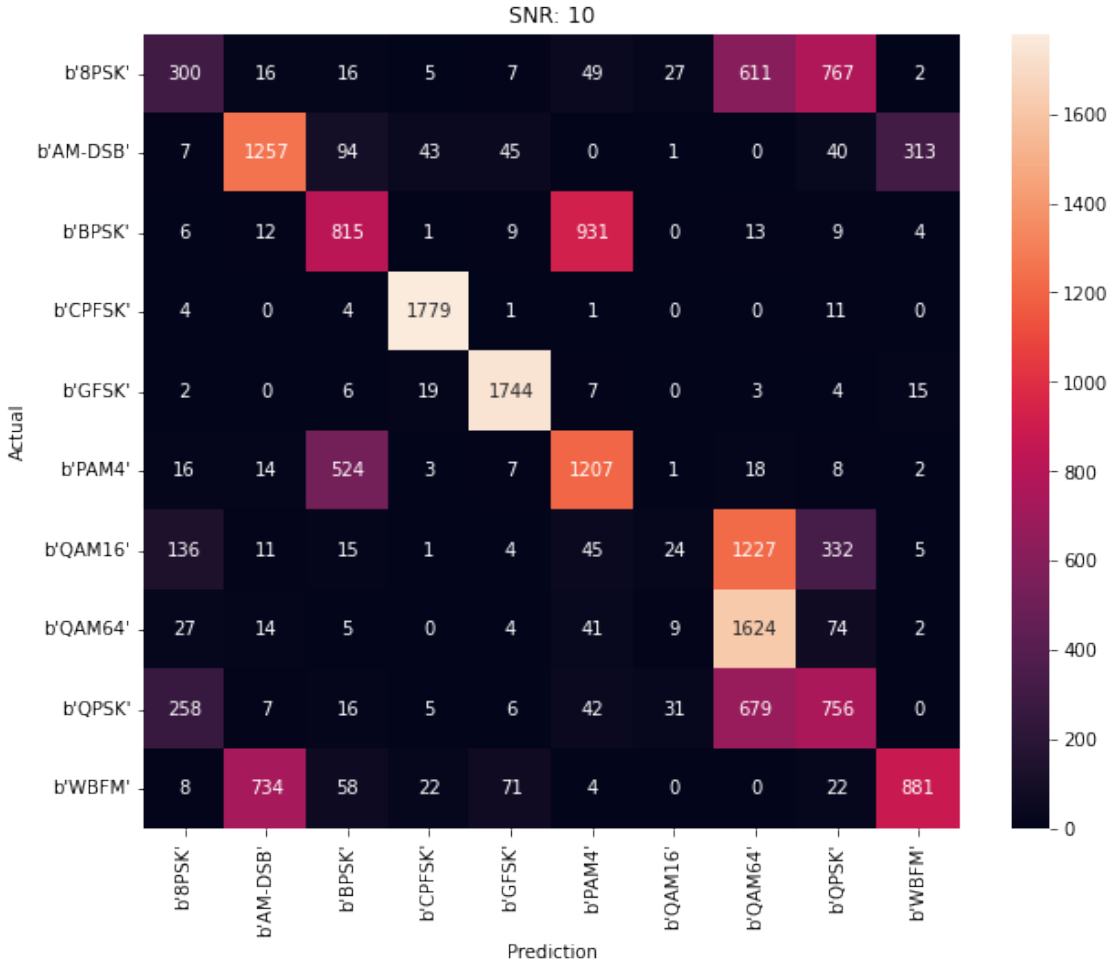
Accuracy at SNR = 6 is 0.5439444444444445%



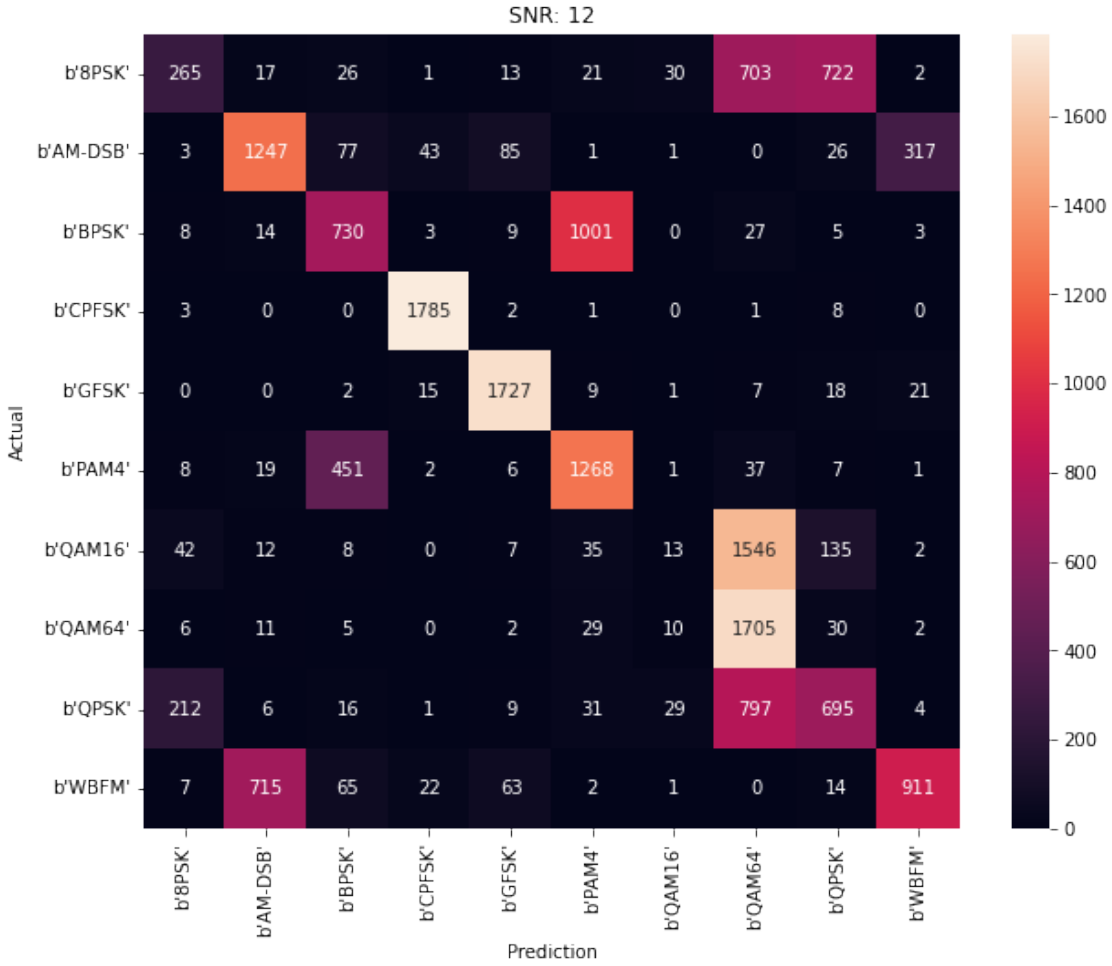

```
Accuracy at SNR = 8 is 0.5782222222222222%
```



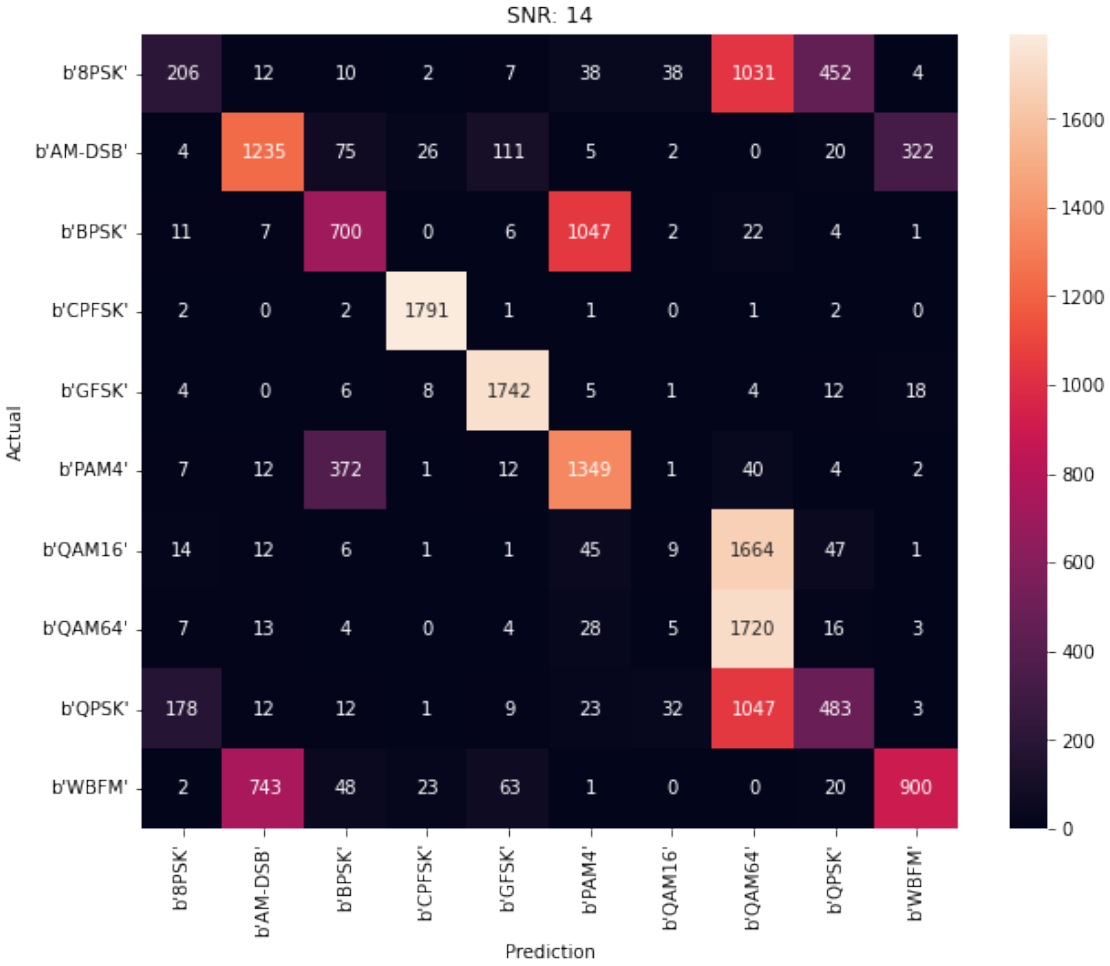
Accuracy at SNR = 10 is 0.5770555555555555%



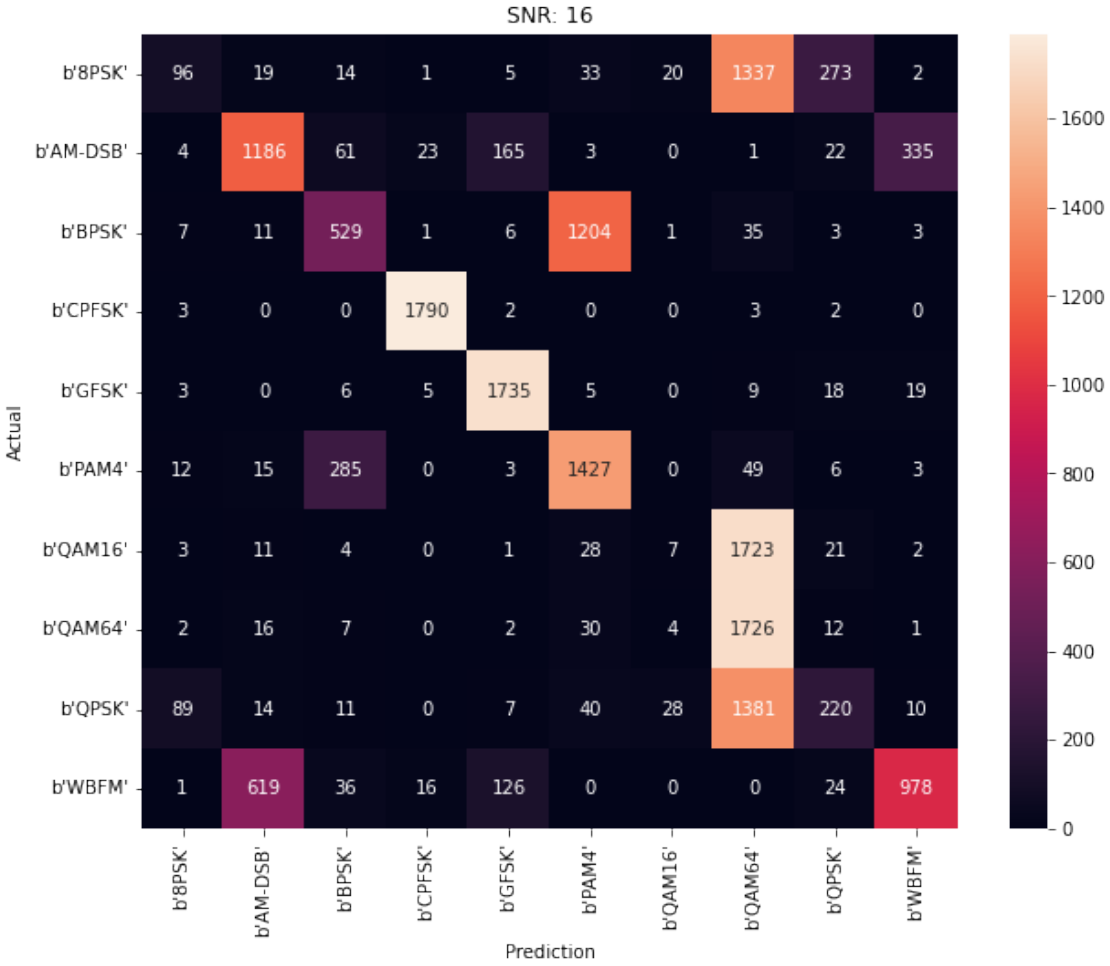

```
Accuracy at SNR = 12 is 0.5747777777777778%
```



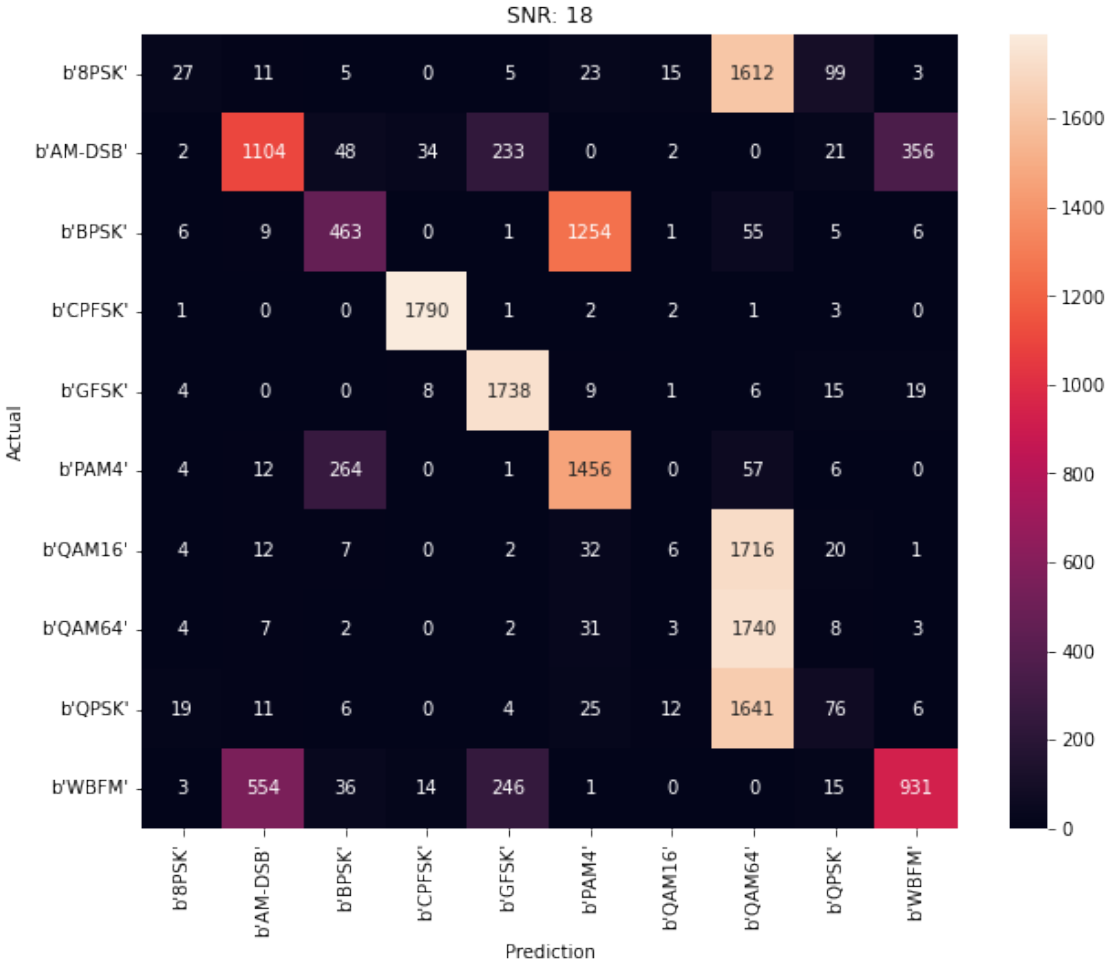

```
Accuracy at SNR = 14 is 0.5630555555555555%
```

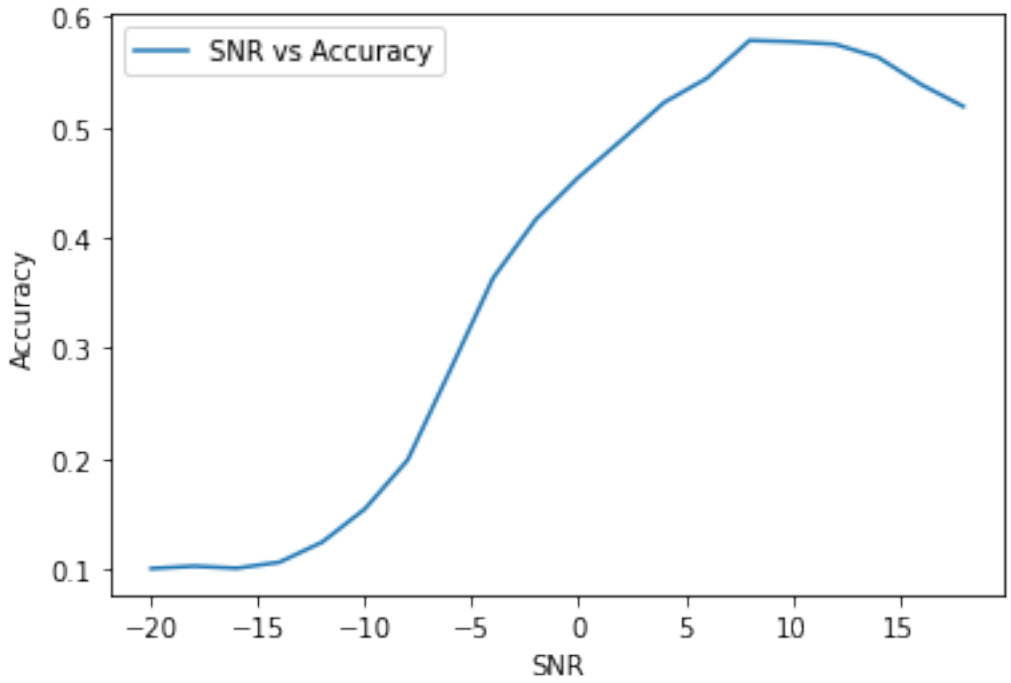


Accuracy at SNR = 16 is 0.5385555555555556%




```
Accuracy at SNR = 18 is 0.5183888888888889%
```


SNR: 18
b'8PSK' 27 11 5 0 5 23 15 1612 99 3
b'AM-DSB' 2 1104 48 34 233 0 2 0 21 356
b'BPSK' 6 9 463 0 1 1254 1 55 5 6
b'CPFSK' 1 0 0 1790 1 2 2 1 3 0
b'GFSK' 4 0 0 8 1738 9 1 6 15 19
b'PAM4' 4 12 264 0 1 1456 0 57 6 0
b'QAM16' 4 12 7 0 2 32 6 1716 20 1
b'QAM64' 4 7 2 0 2 31 3 1740 8 3
b'QPSK' 19 11 6 0 4 25 12 1641 76 6
b'WBFM' 3 554 36 14 246 1 0 0 15 931
Actual
b'8PSK' b'AM-DSB' b'BPSK' b'CPFSK' b'GFSK' b'PAM4' b'QAM16' b'QAM64' b'QPSK' b'WBFM'
Prediction
1600 1400 1200 1000 800 600 400 200 0



7.4 LSTM Model

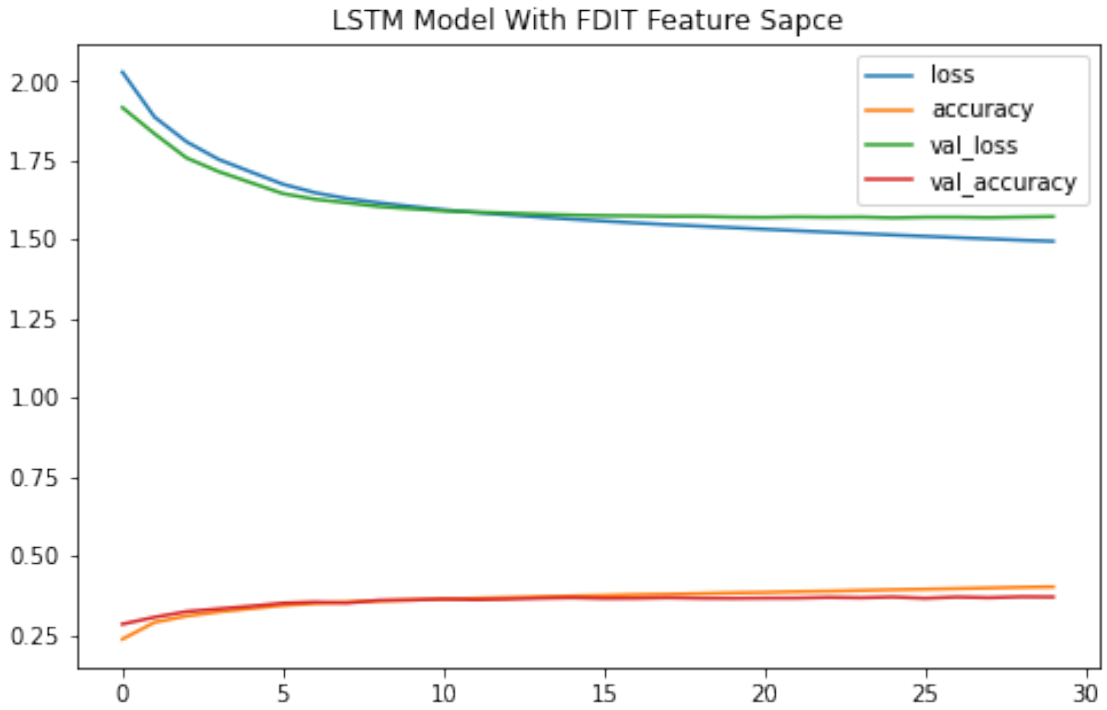
[ ]:
```
learning_rate = 0.001
batch_size = 512
epochs = 200
```

[ ]:
```
lstm_model = Sequential()
lstm_model.add(LSTM(256))
lstm_model.add(Dropout(0.2))
lstm_model.add(Dense(10, activation='softmax'))
lstm_model.compile(loss=tf.keras.losses.CategoricalCrossentropy(),␣
 ↪metrics='accuracy', optimizer=tf.keras.optimizers.
 ↪Adam(learning_rate=learning_rate))
```

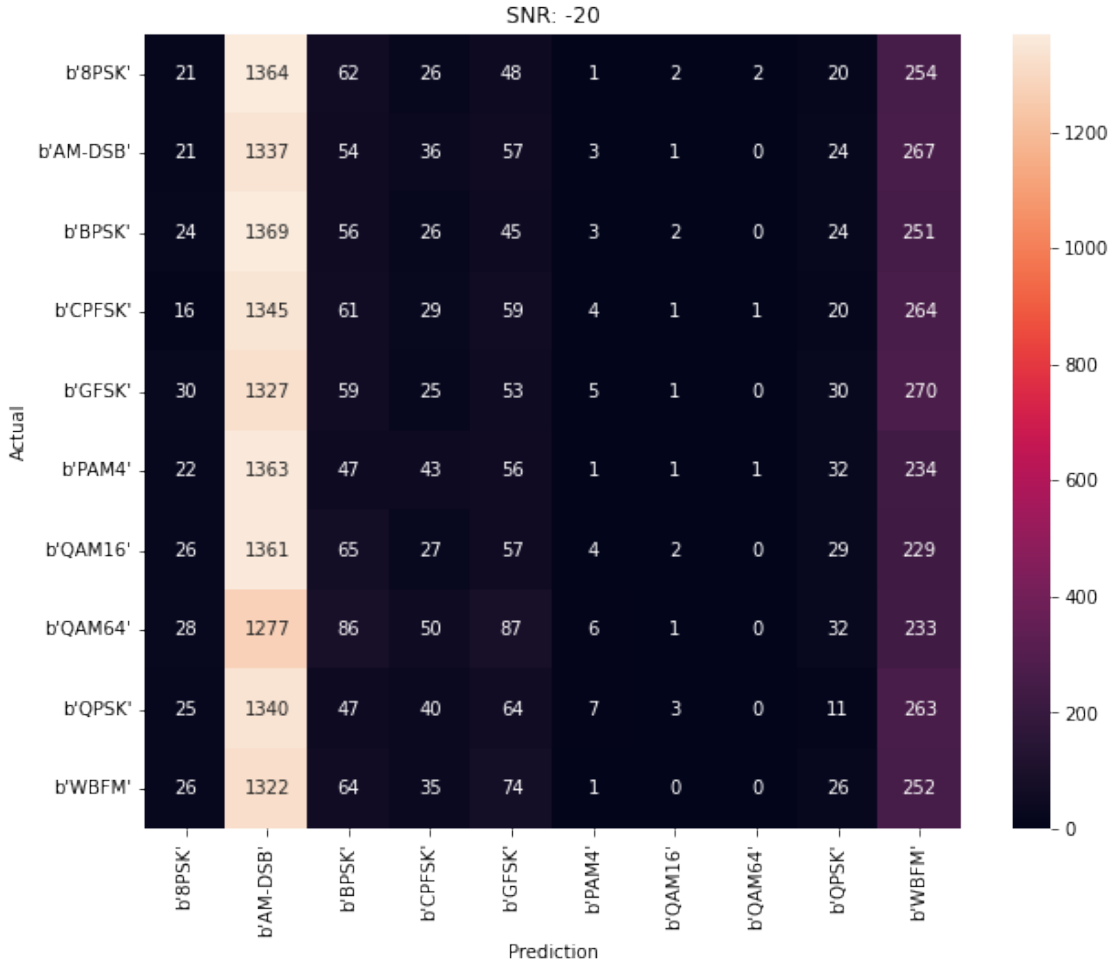
[ ]:
```
es = tf.keras.callbacks.EarlyStopping(monitor="val_loss", patience=5,␣
 ↪restore_best_weights=True,)
checkpointer = ModelCheckpoint(filepath='saved_models/lstm_fdit_classification.
 ↪hdf5', verbose=1, save_best_only=True)

with tf.device('/device:GPU:0'):
  history = lstm_model.fit(fdit_training_data, training_onehot,␣
 ↪batch_size=batch_size, epochs=epochs, validation_data=(fdit_validation_data,␣
 ↪validation_onehot), callbacks=[es, checkpointer], verbose=1)
```

```
Epoch 1/200
1550/1559 [============================>.] - ETA: 0s - loss: 2.0299 - accuracy:
0.2357
Epoch 1: val_loss improved from inf to 1.91719, saving model to
saved_models/lstm_fdit_classification.hdf5
1559/1559 [==============================] - 9s 5ms/step - loss: 2.0293 -
accuracy: 0.2359 - val_loss: 1.9172 - val_accuracy: 0.2834

Epoch 30: val_loss did not improve from 1.56859
1559/1559 [==============================] - 7s 5ms/step - loss: 1.4944 -
accuracy: 0.4012 - val_loss: 1.5724 - val_accuracy: 0.3691
```

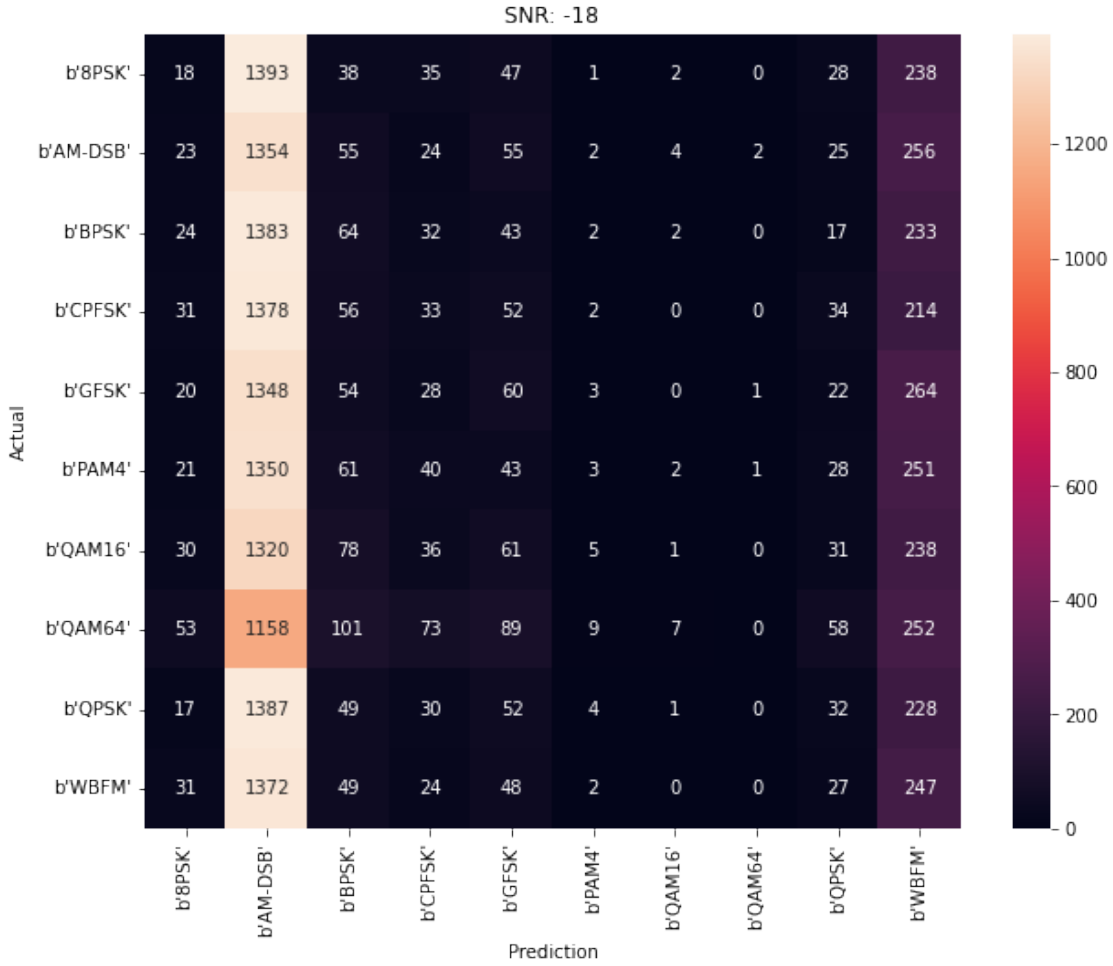
[ ]:
```
plot_model_history(history, 'LSTM Model With FDIT Feature Sapce')
model_scoring(lstm_model, history, fdit_testing_data, testing_pair_labels)
```



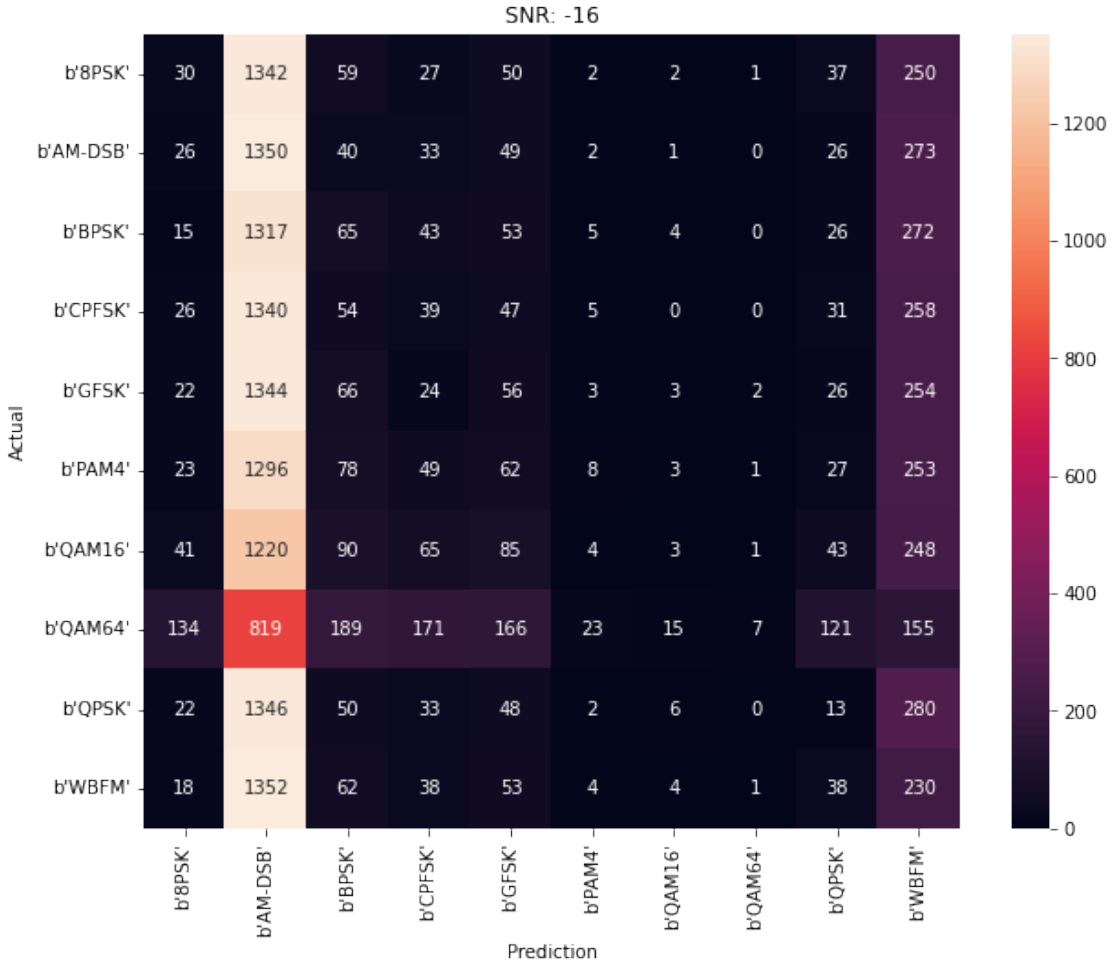

```
Accuracy at SNR = -20 is 0.09788888888888889%
```



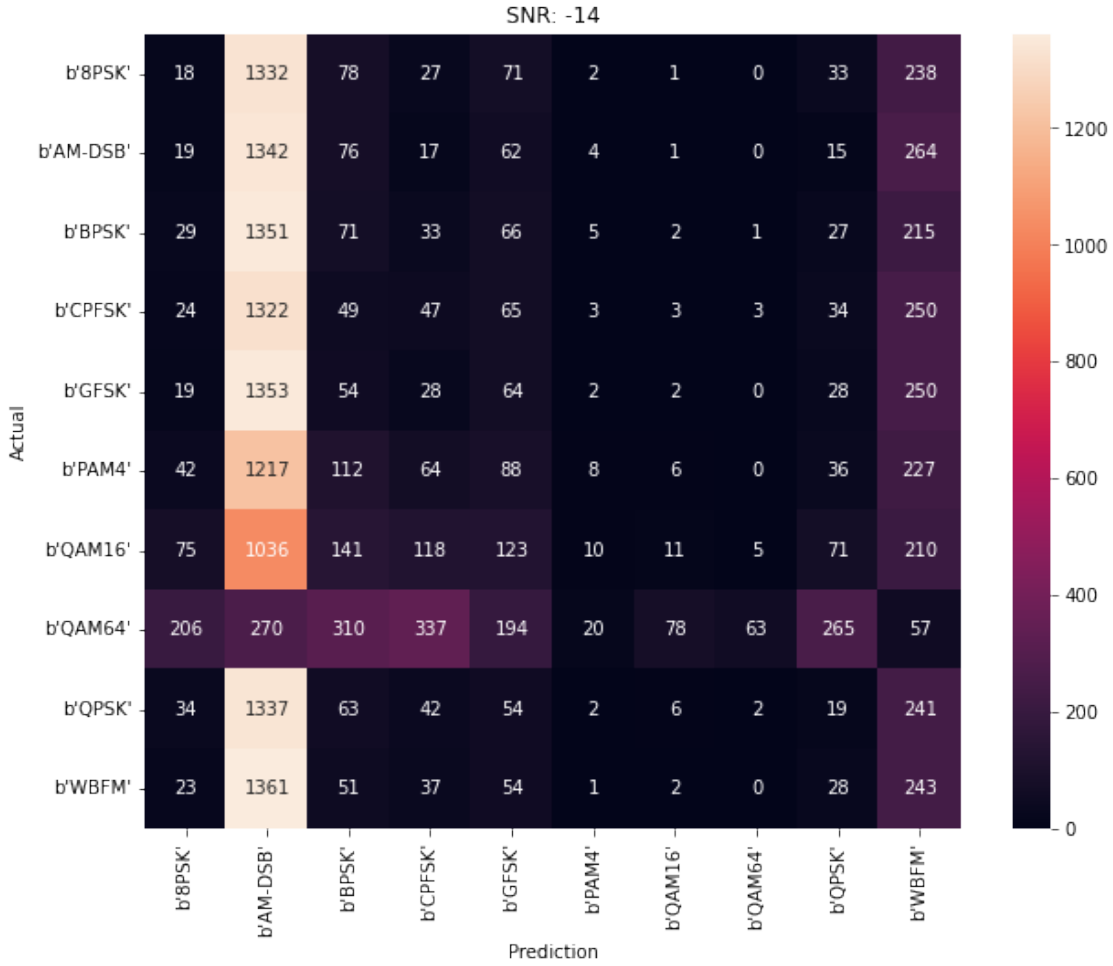

```
Accuracy at SNR = -18 is 0.10066666666666667%
```



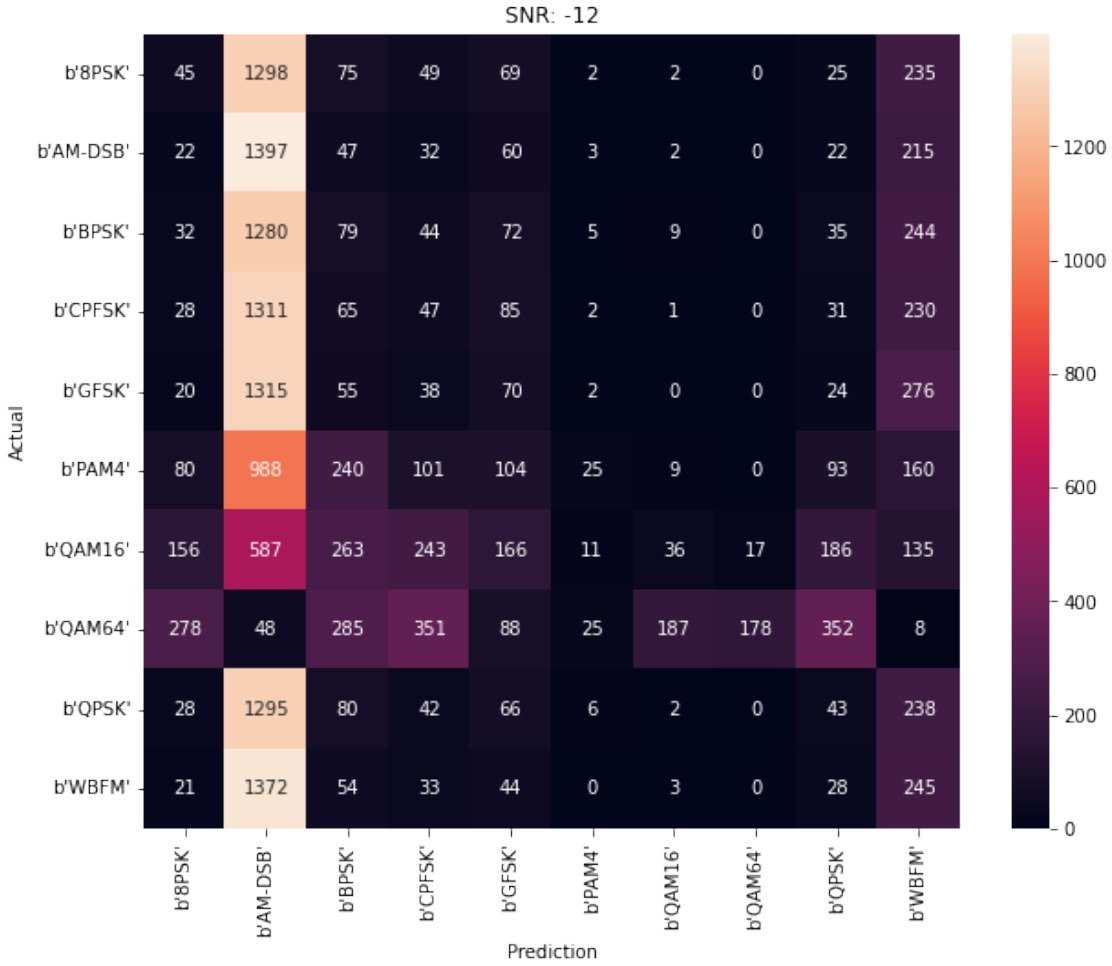

```
Accuracy at SNR = -16 is 0.10005555555555555%
```



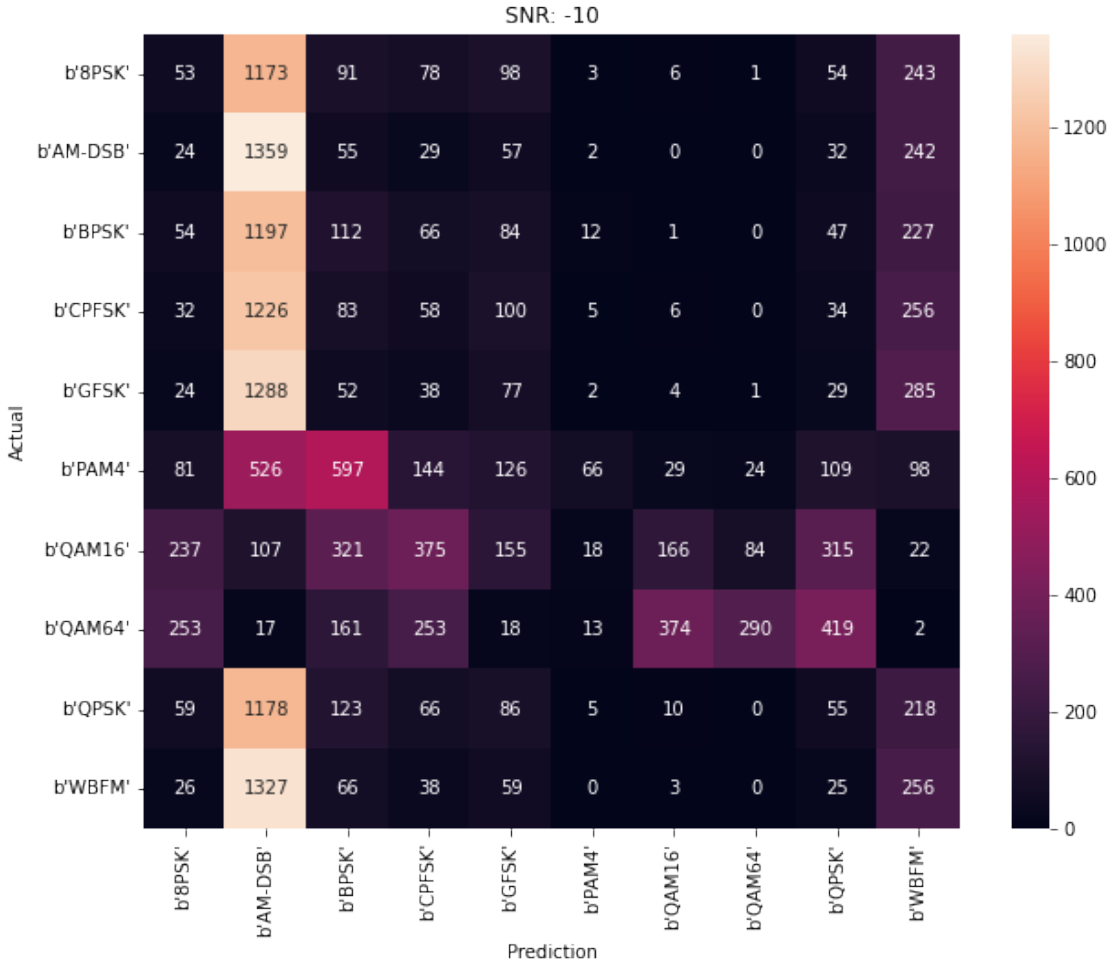

```
Accuracy at SNR = -14 is 0.10477777777777778%
```



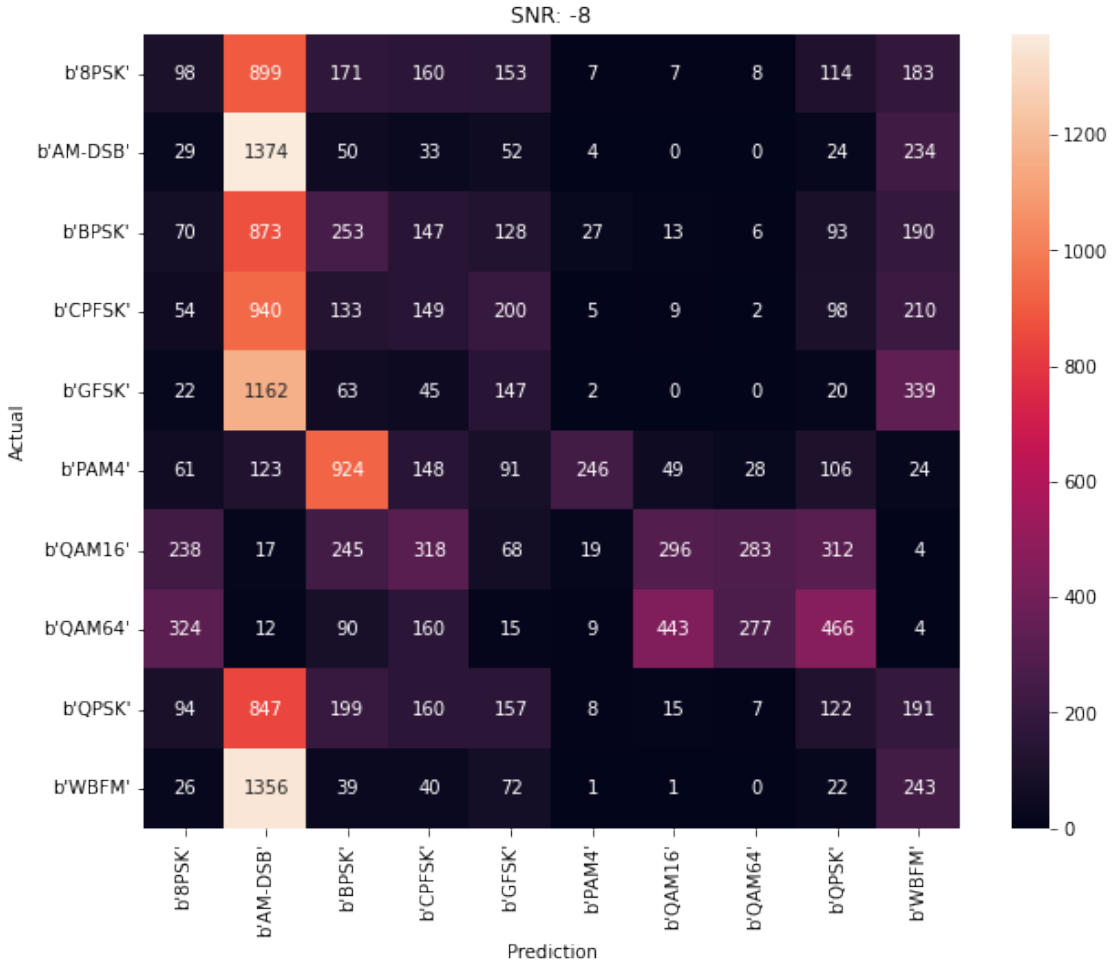

```
Accuracy at SNR = -12 is 0.12027777777777778%
```



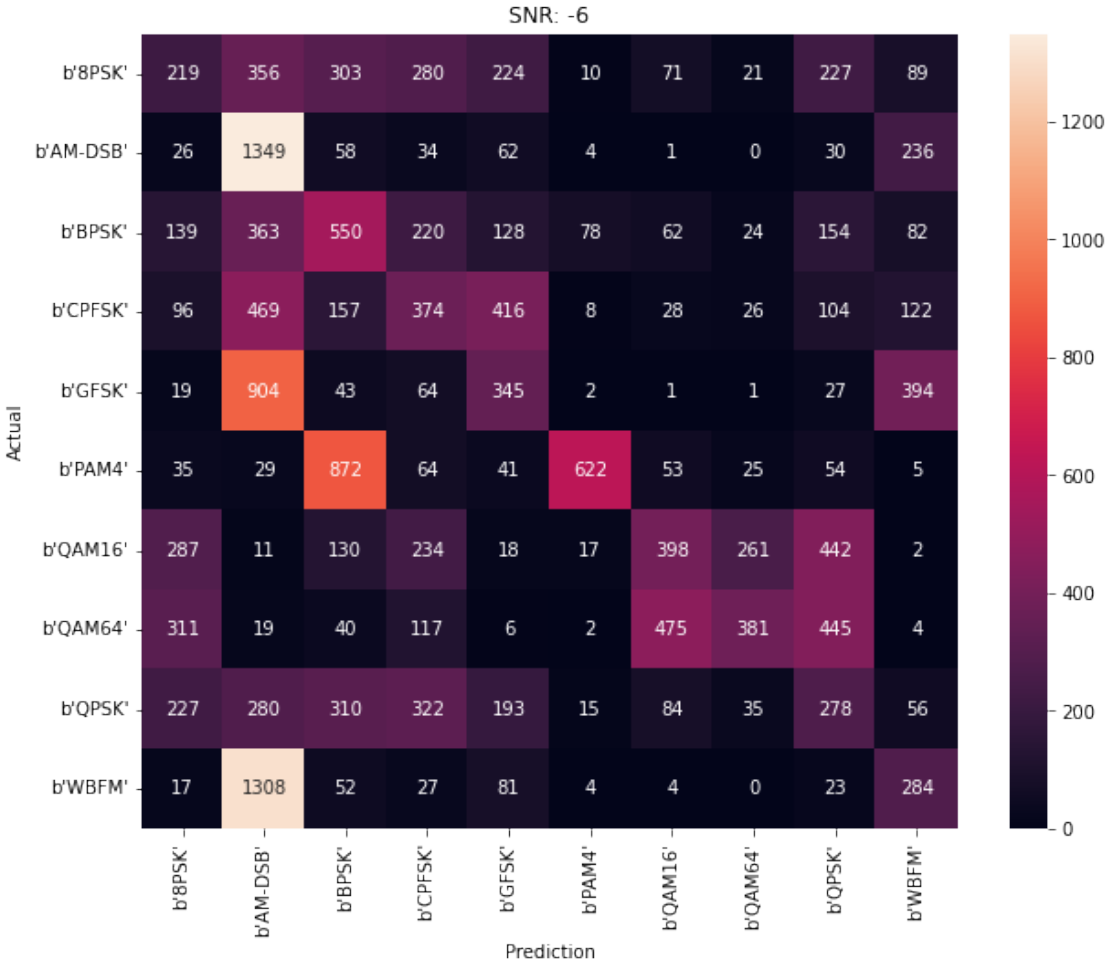
Accuracy at SNR = -10 is 0.13844444444444445%



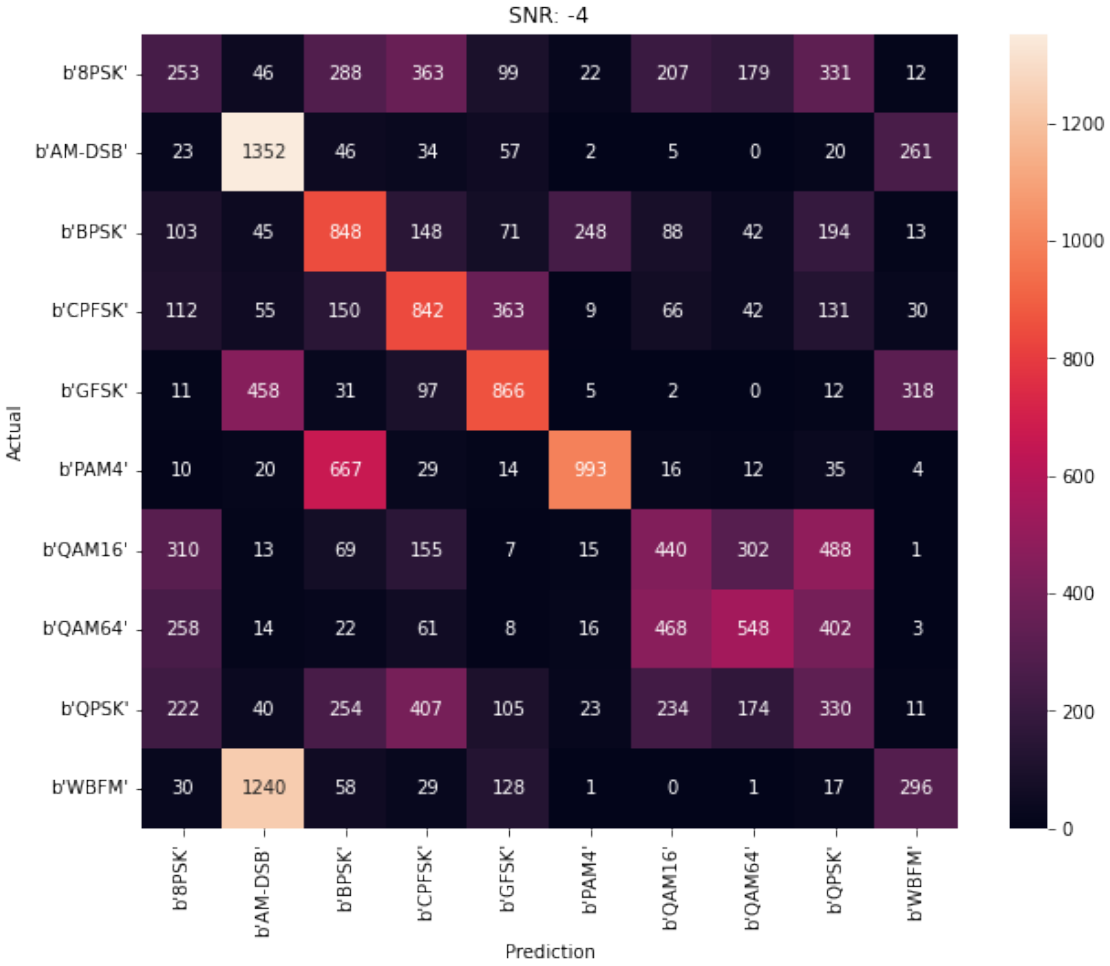

```
Accuracy at SNR = -8 is 0.17805555555555555%
```



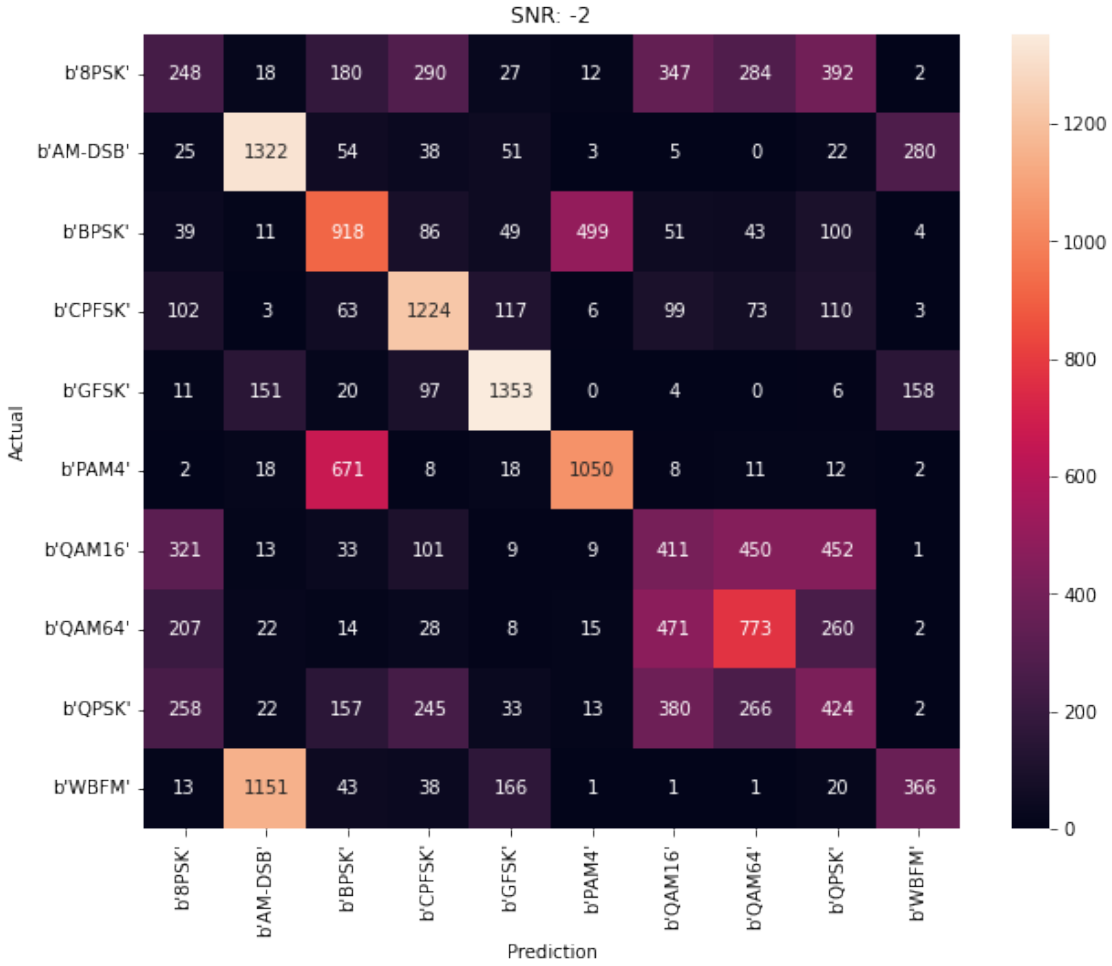

```
Accuracy at SNR = -6 is 0.26666666666666666%
```



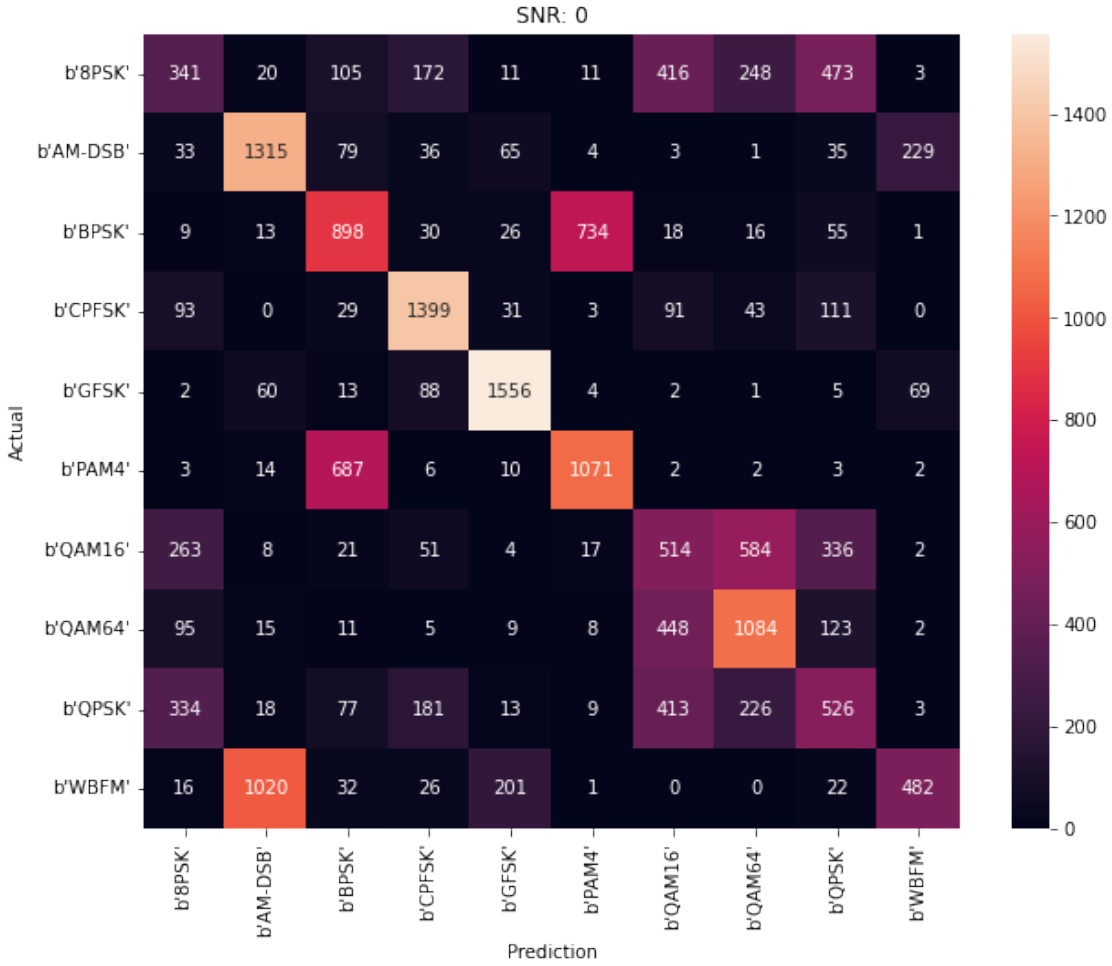

```
Accuracy at SNR = -4 is 0.376%
```



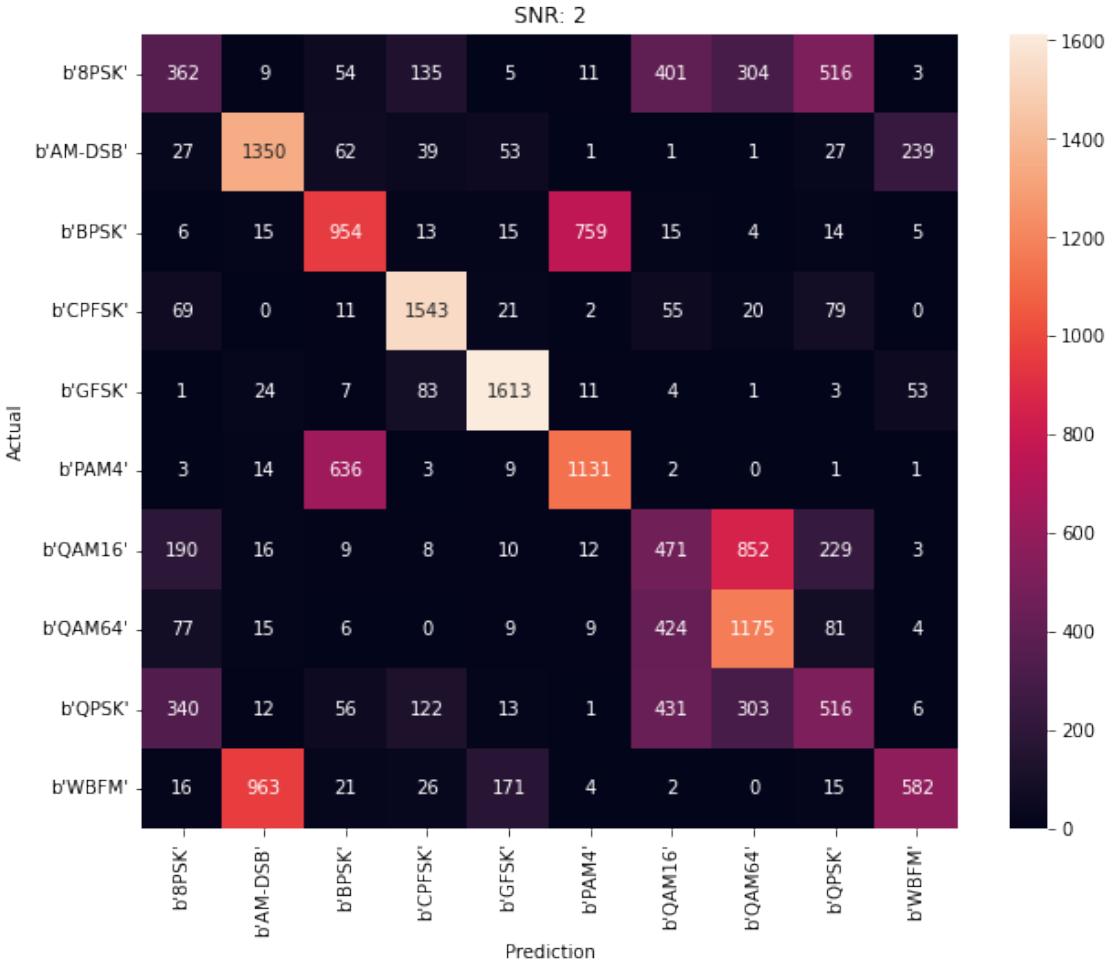
Accuracy at SNR = -2 is 0.4493888888888889%



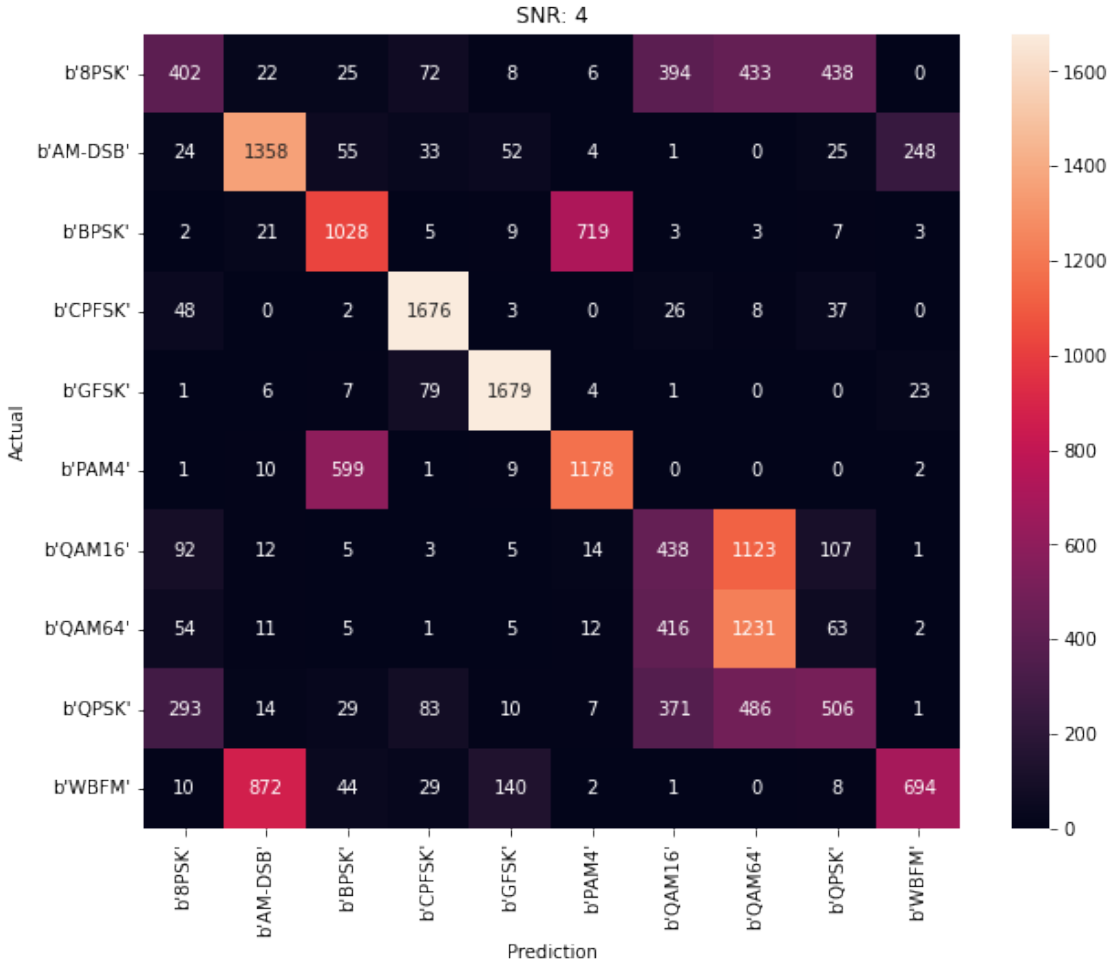

```
Accuracy at SNR = 0 is 0.5103333333333333%
```



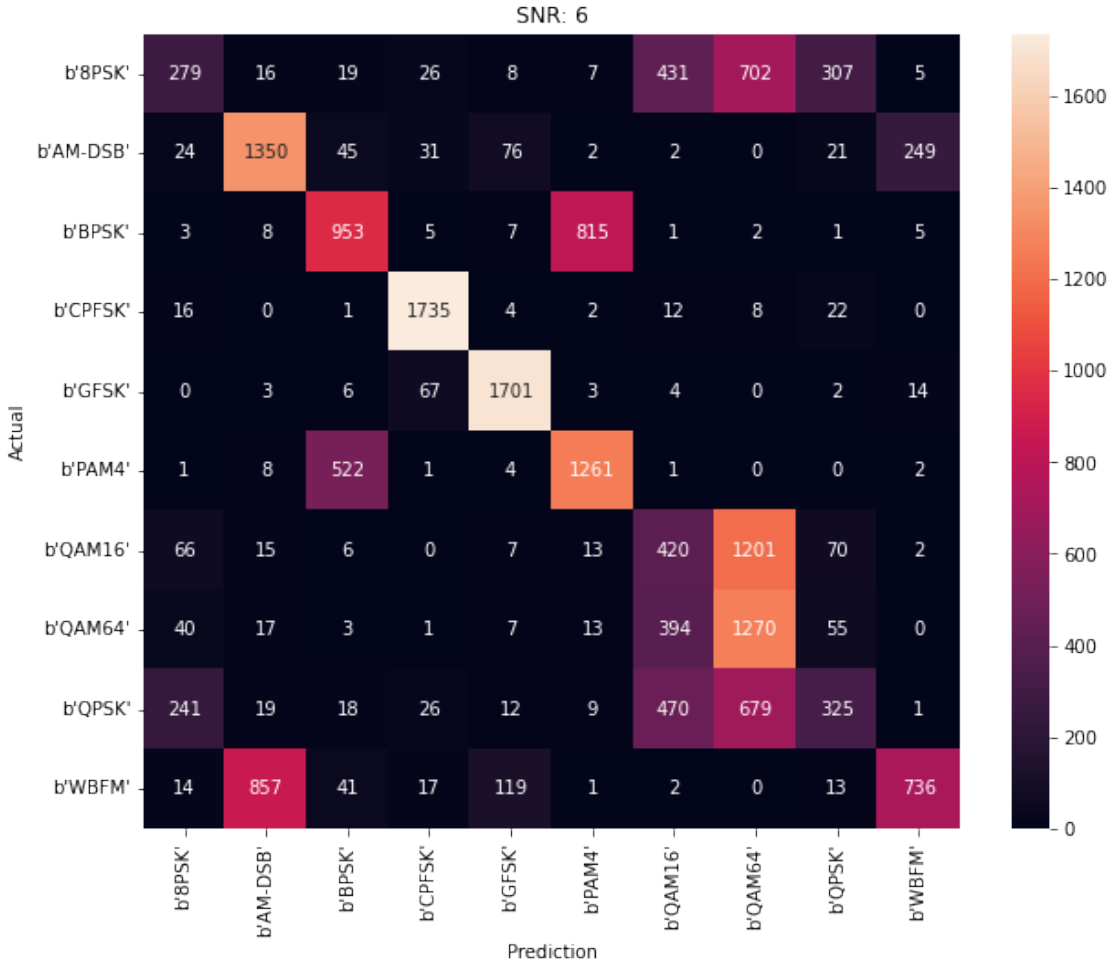

```
Accuracy at SNR = 2 is 0.5387222222222222%
```



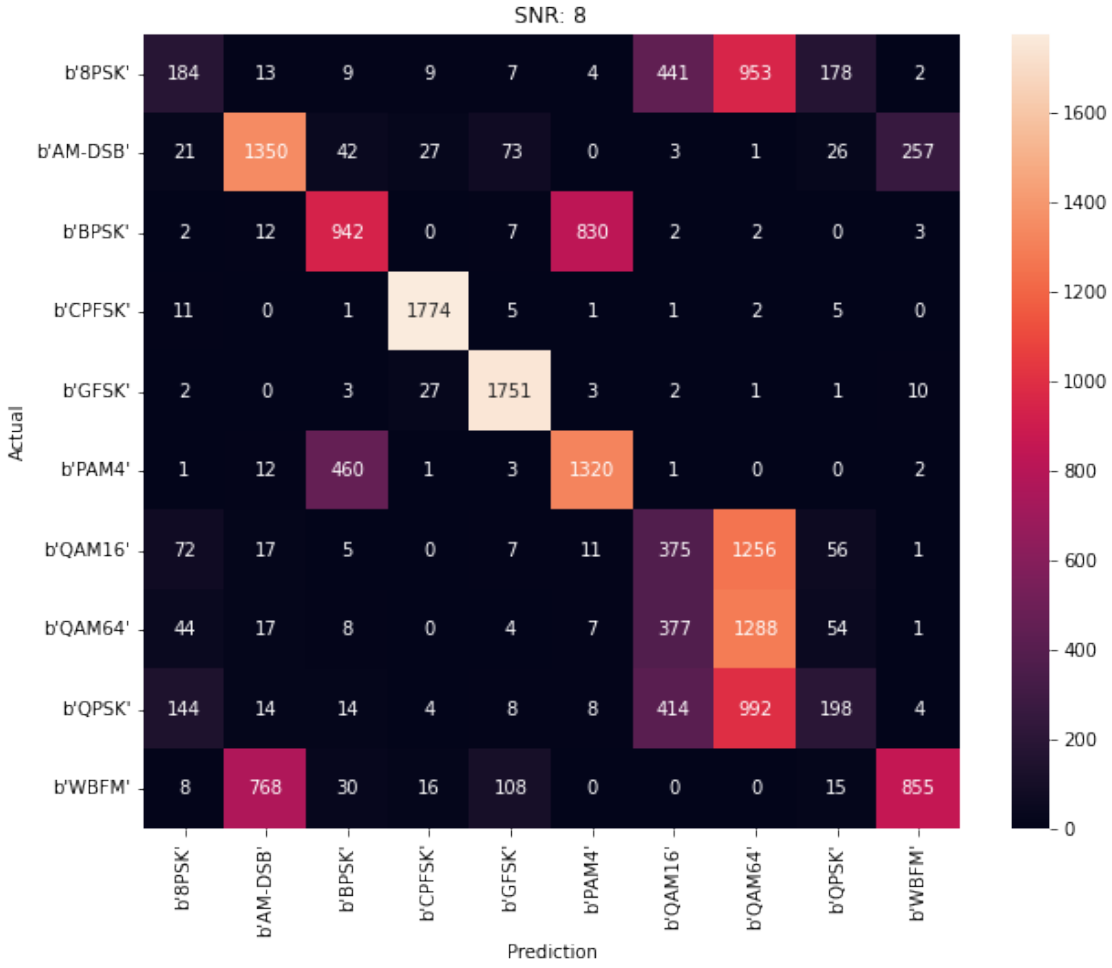
Accuracy at SNR = 4 is 0.5661111111111111%



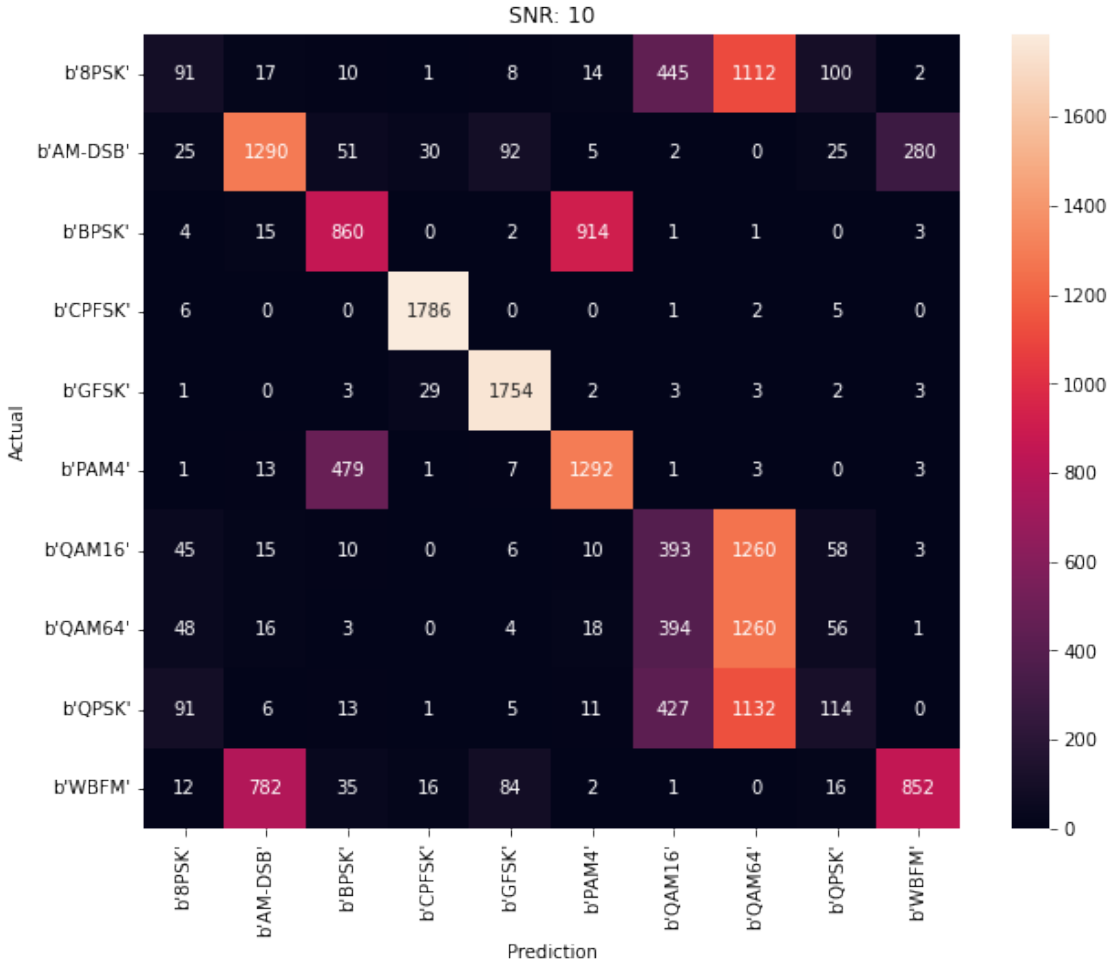

```
Accuracy at SNR = 6 is 0.5572222222222222%
```



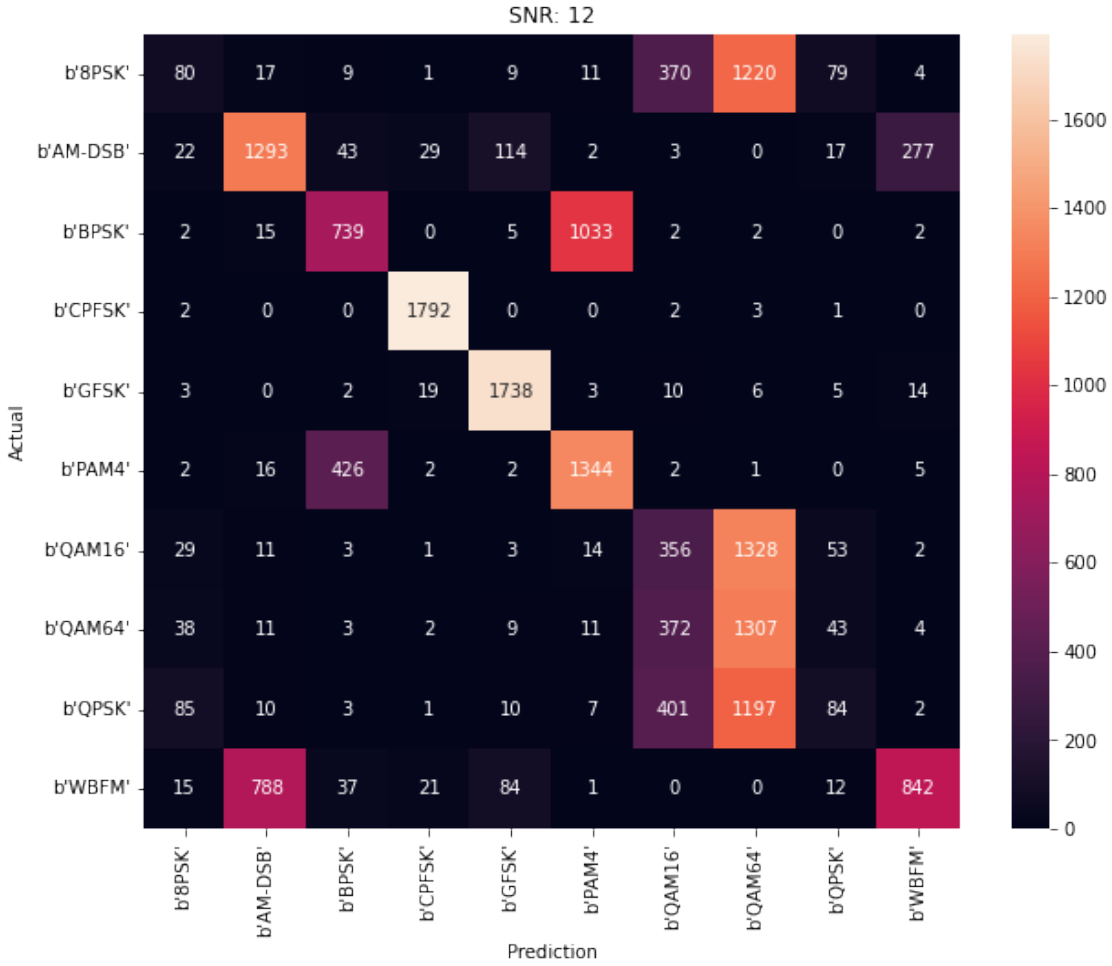

```
Accuracy at SNR = 8 is 0.5576111111111111%
```



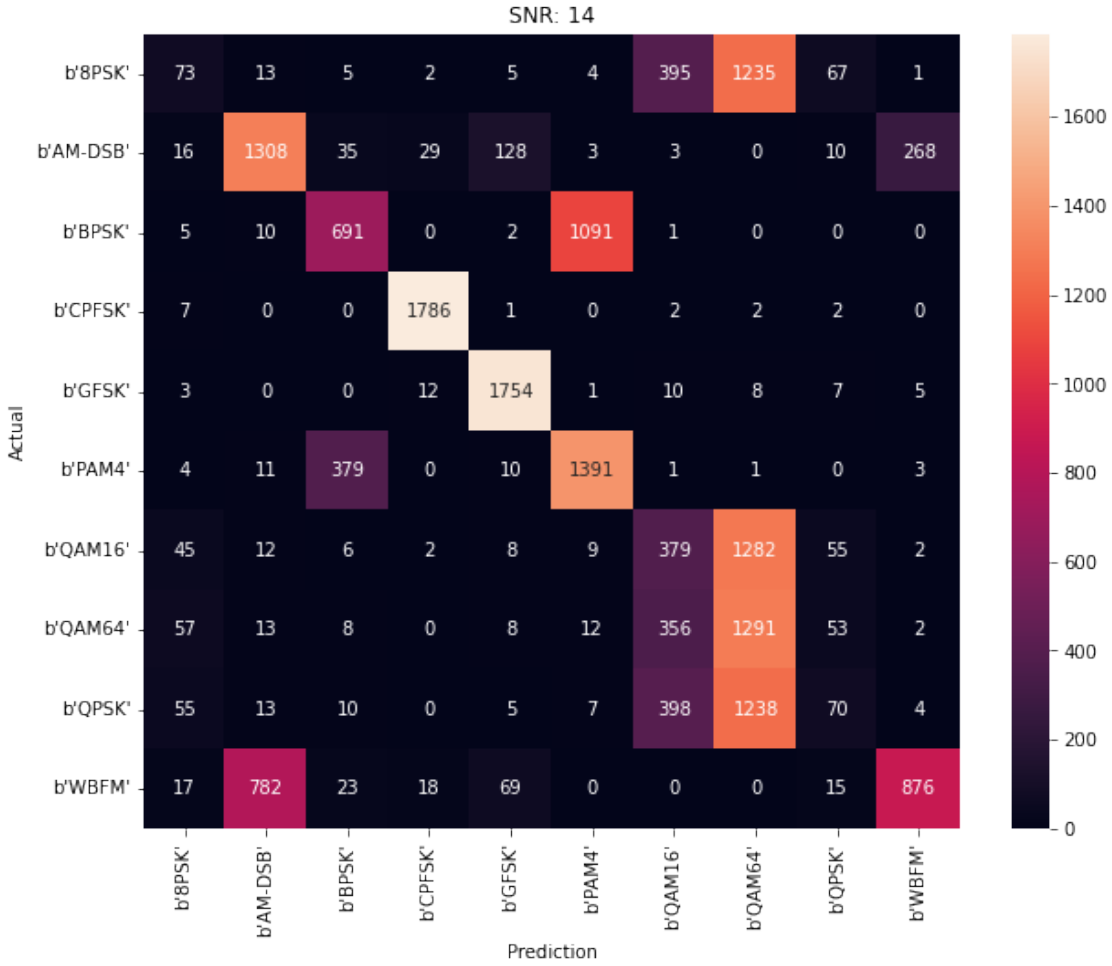
Accuracy at SNR = 10 is 0.5384444444444444%



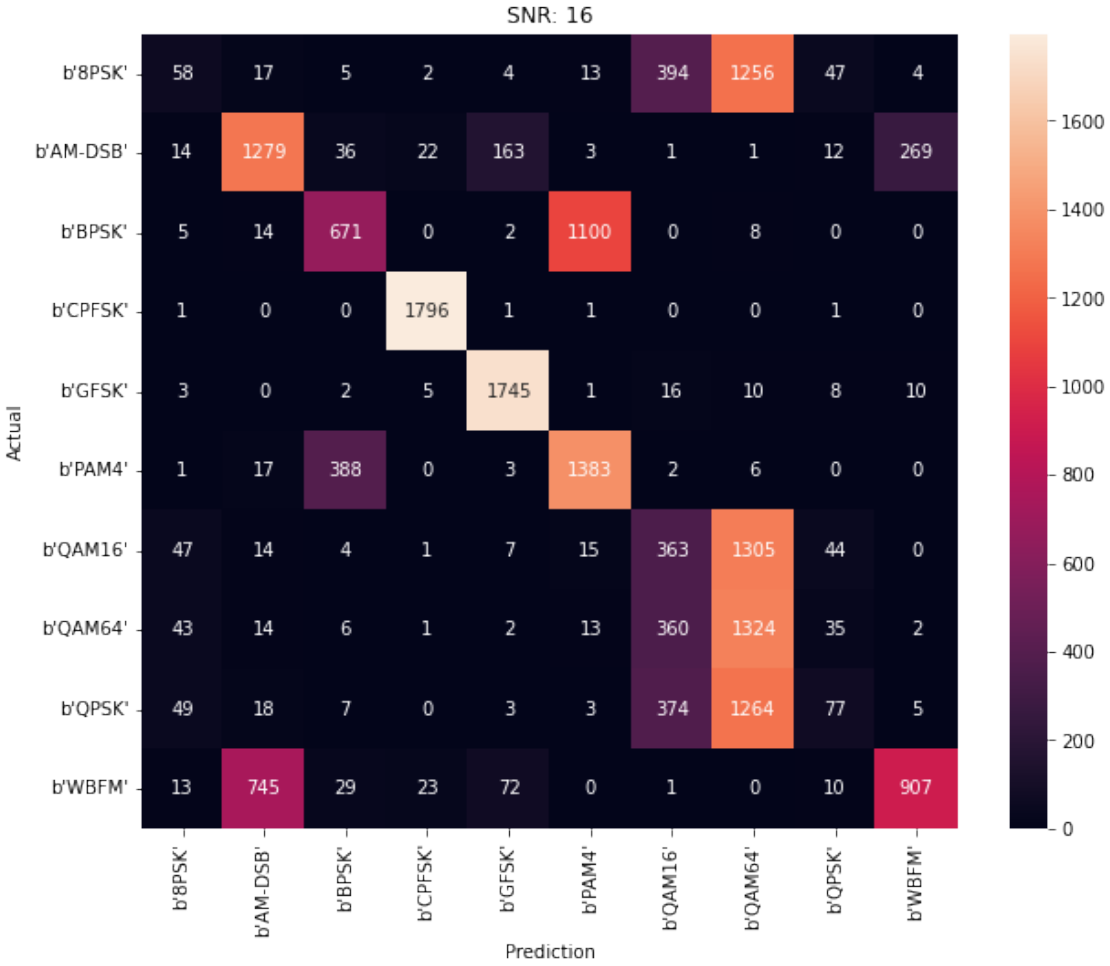

```
Accuracy at SNR = 12 is 0.5319444444444444%
```



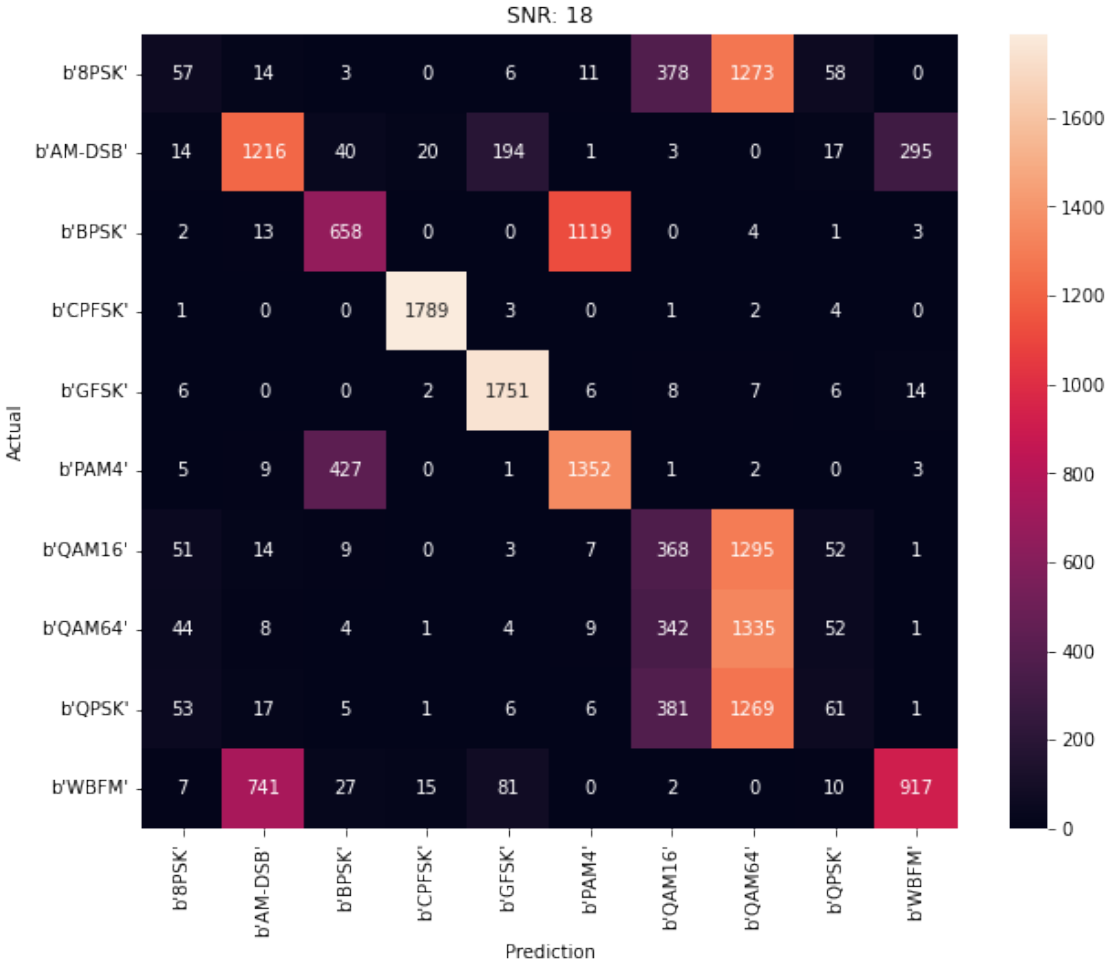

```
Accuracy at SNR = 14 is 0.5343888888888889%
```

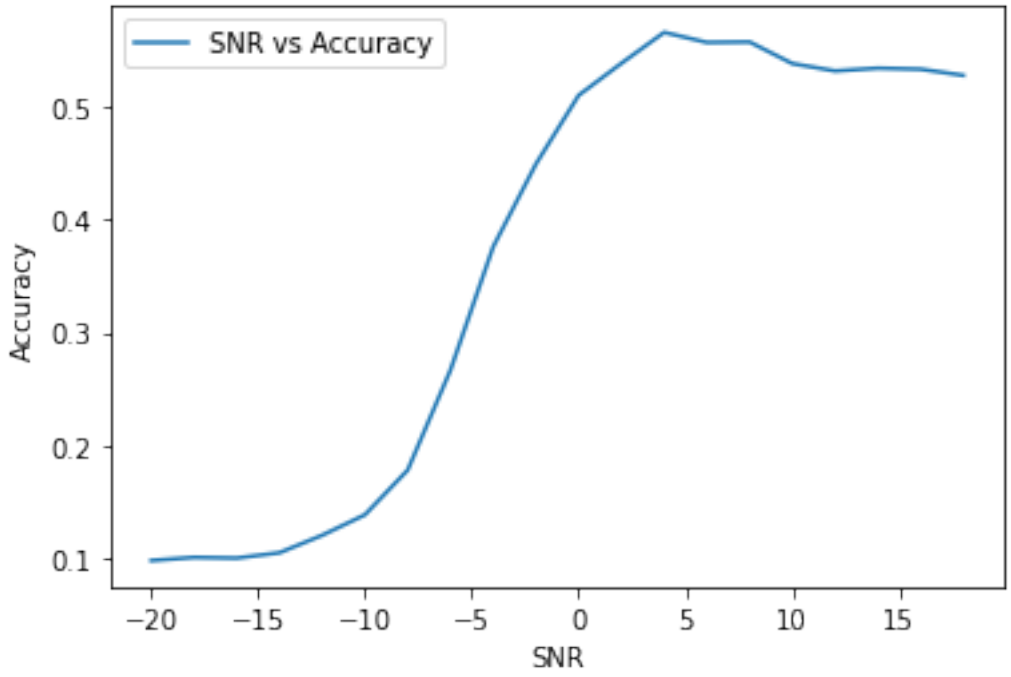



```
Accuracy at SNR = 16 is 0.5335%
```




```
Accuracy at SNR = 18 is 0.528%
```


SNR: 18
b'8PSK' 57 14 3 0 6 11 378 1273 58 0
b'AM-DSB' 14 1216 40 20 194 1 3 0 17 295
b'BPSK' 2 13 658 0 0 1119 0 4 1 3
b'CPFSK' 1 0 0 1789 3 0 1 2 4 0
b'GFSK' 6 0 0 2 1751 6 8 7 6 14
b'PAM4' 5 9 427 0 1 1352 1 2 0 3
b'QAM16' 51 14 9 0 3 7 368 1295 52 1
b'QAM64' 44 8 4 1 4 9 342 1335 52 1
b'QPSK' 53 17 5 1 6 6 381 1269 61 1
b'WBFM' 7 741 27 15 81 0 2 0 10 917
Actual
b'8PSK' b'AM-DSB' b'BPSK' b'CPFSK' b'GFSK' b'PAM4' b'QAM16' b'QAM64' b'QPSK' b'WBFM'
Prediction
1600 1400 1200 1000 800 600 400 200 0



8 Integrated Features Space

[29]:
```
fiit_training_data = integrate.cumtrapz(training_data, initial=0)
fiit_validation_data = integrate.cumtrapz(validation_data, initial=0)
fiit_testing_data = integrate.cumtrapz(testing_data, initial=0)
```

[30]:
```
print('fiit training data shape:', fiit_training_data.shape)
print('fiit validation data shape:', fiit_validation_data.shape)
print('fiit testing data shape:', fiit_testing_data.shape)
```

```
fiit training data shape: (798000, 2, 128)
fiit validation data shape: (42000, 2, 128)
fiit testing data shape: (360000, 2, 128)
```

8.1 CNN Model

[29]:
```
fiit_training_data, fiit_validation_data, fiit_testing_data =␣
↪reshape_data_for_cnn(fiit_training_data, fiit_validation_data,␣
↪fiit_testing_data)
```

[30]:
```
print('training data shape:', fiit_training_data.shape)
print('validation data shape:', fiit_validation_data.shape)
print('testing data shape:', fiit_testing_data.shape)
```

```
training data shape: (798000, 2, 128, 1)
validation data shape: (42000, 2, 128, 1)
testing data shape: (360000, 2, 128, 1)
```

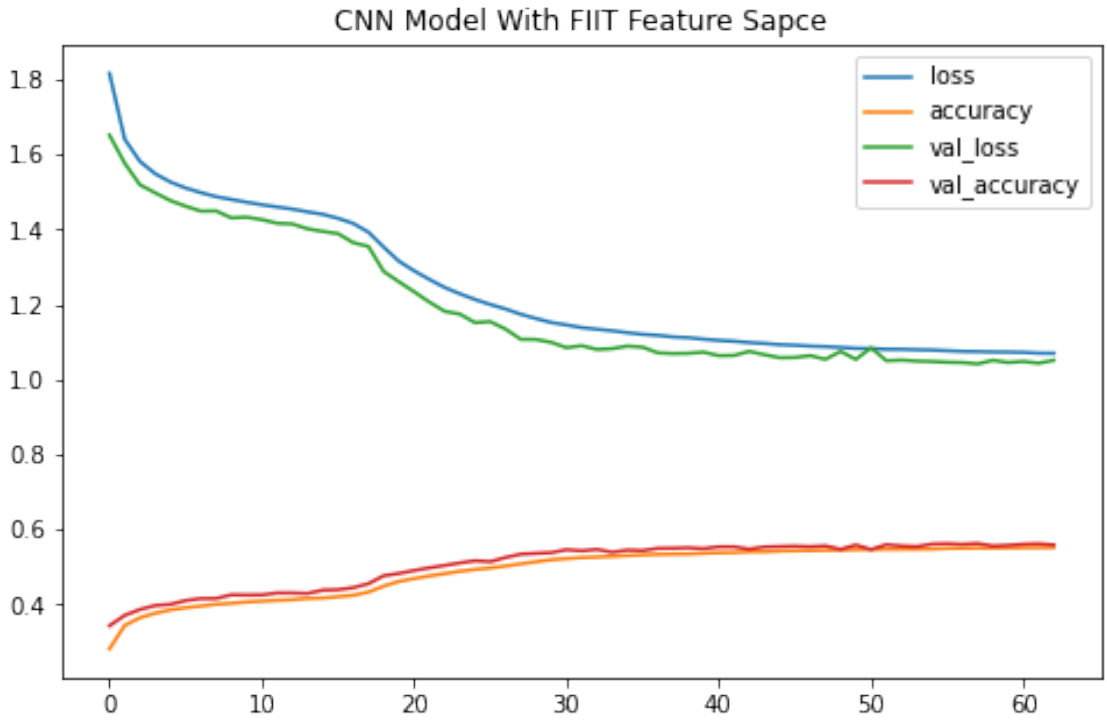
[31]:
```
learning_rate = 0.001
batch_size = 512
epochs = 200
```

[32]:
```
cnn_model = Sequential()
cnn_model.add(Conv2D(256, 3, activation='relu', padding='same'))
cnn_model.add(Dropout(0.5))
cnn_model.add(Conv2D(64, 3, strides=2, activation='relu', padding='same'))
cnn_model.add(Dropout(0.5))
cnn_model.add(Flatten())
cnn_model.add(Dense(128, activation='relu' ))
cnn_model.add(Dense(10,  activation='softmax'))
cnn_model.compile(loss=tf.keras.losses.CategoricalCrossentropy(),␣
 ↪metrics='accuracy', optimizer=tf.keras.optimizers.
 ↪Adam(learning_rate=learning_rate))
```

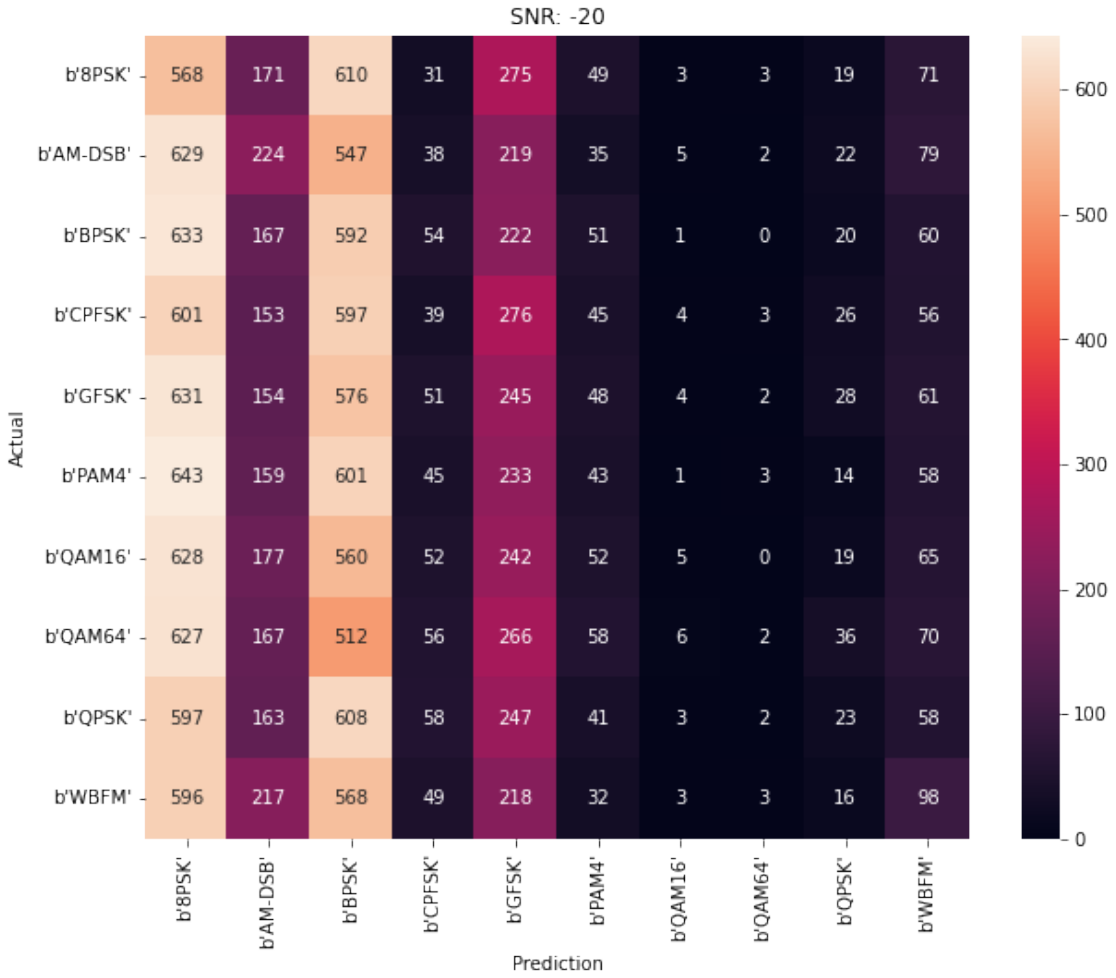
[33]:
```
es = tf.keras.callbacks.EarlyStopping(monitor="val_loss", patience=5,␣
 ↪restore_best_weights=True,)
checkpointer = ModelCheckpoint(filepath='saved_models/cnn_fiit_classification.
 ↪hdf5', verbose=1, save_best_only=True)

with tf.device('/device:GPU:0'):
  history = cnn_model.fit(fiit_training_data, training_onehot,␣
 ↪batch_size=batch_size, epochs=epochs, validation_data=(fiit_validation_data,␣
 ↪validation_onehot), callbacks=[es, checkpointer], verbose=1)
```

```
Epoch 1/200
1559/1559 [==============================] - ETA: 0s - loss: 1.8168 - accuracy:
0.2821
Epoch 1: val_loss improved from inf to 1.65205, saving model to
saved_models/cnn_fiit_classification.hdf5
1559/1559 [==============================] - 78s 42ms/step - loss: 1.8168 -
accuracy: 0.2821 - val_loss: 1.6521 - val_accuracy: 0.3437

Epoch 63: val_loss did not improve from 1.04195
1559/1559 [==============================] - 67s 43ms/step - loss: 1.0702 -
accuracy: 0.5525 - val_loss: 1.0517 - val_accuracy: 0.5593
```

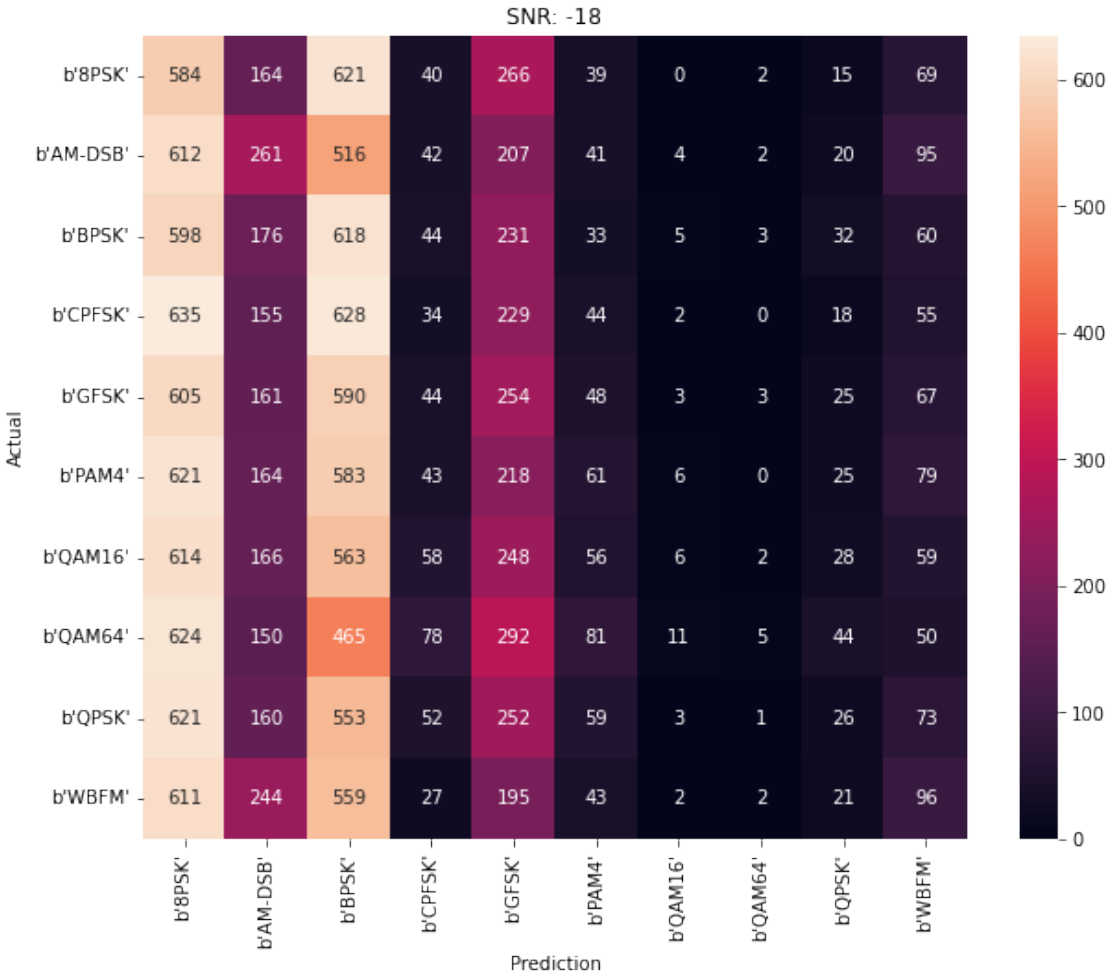
[34]:
```
plot_model_history(history, 'CNN Model With FIIT Feature Sapce')
model_scoring(cnn_model, history, fiit_testing_data, testing_pair_labels)
```



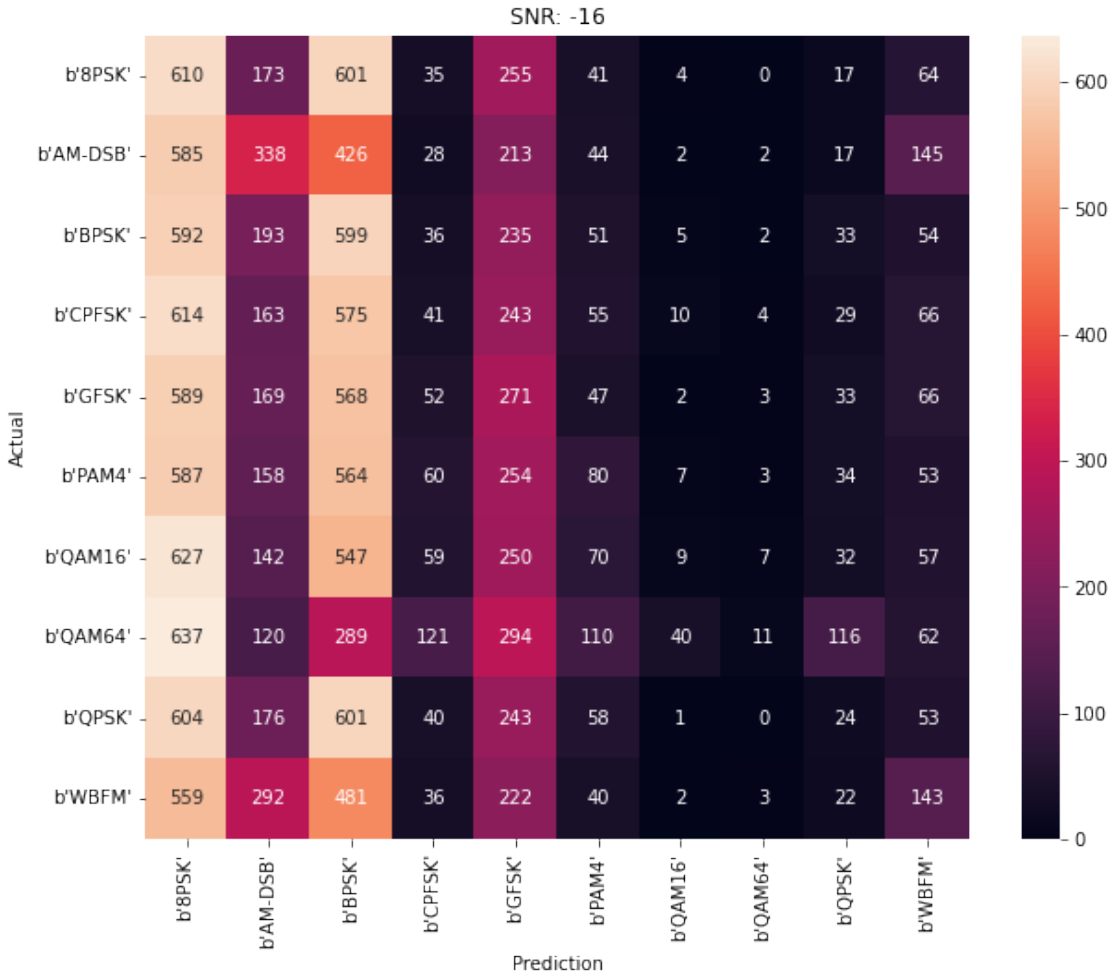

```
Accuracy at SNR = -20 is 0.10216666666666667%
```



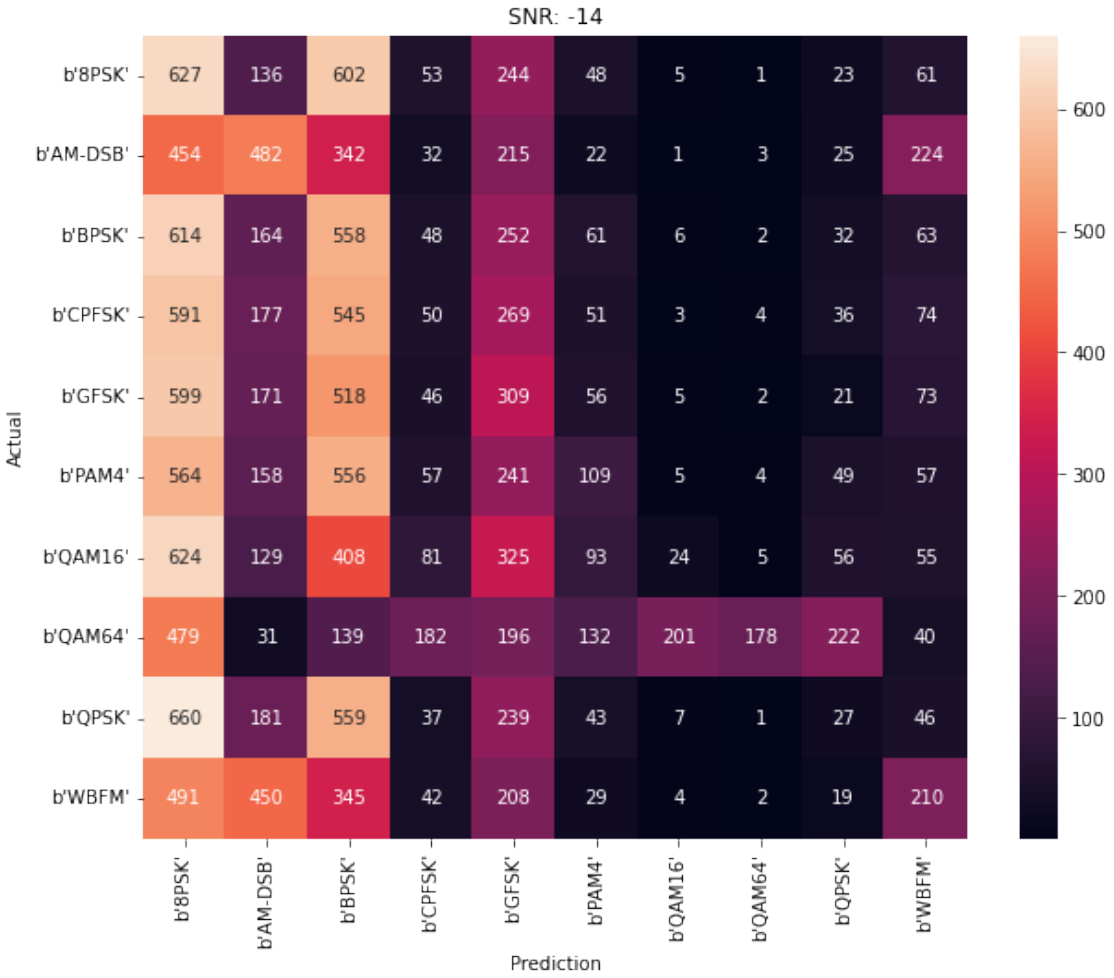

```
Accuracy at SNR = -18 is 0.10805555555555556%
```



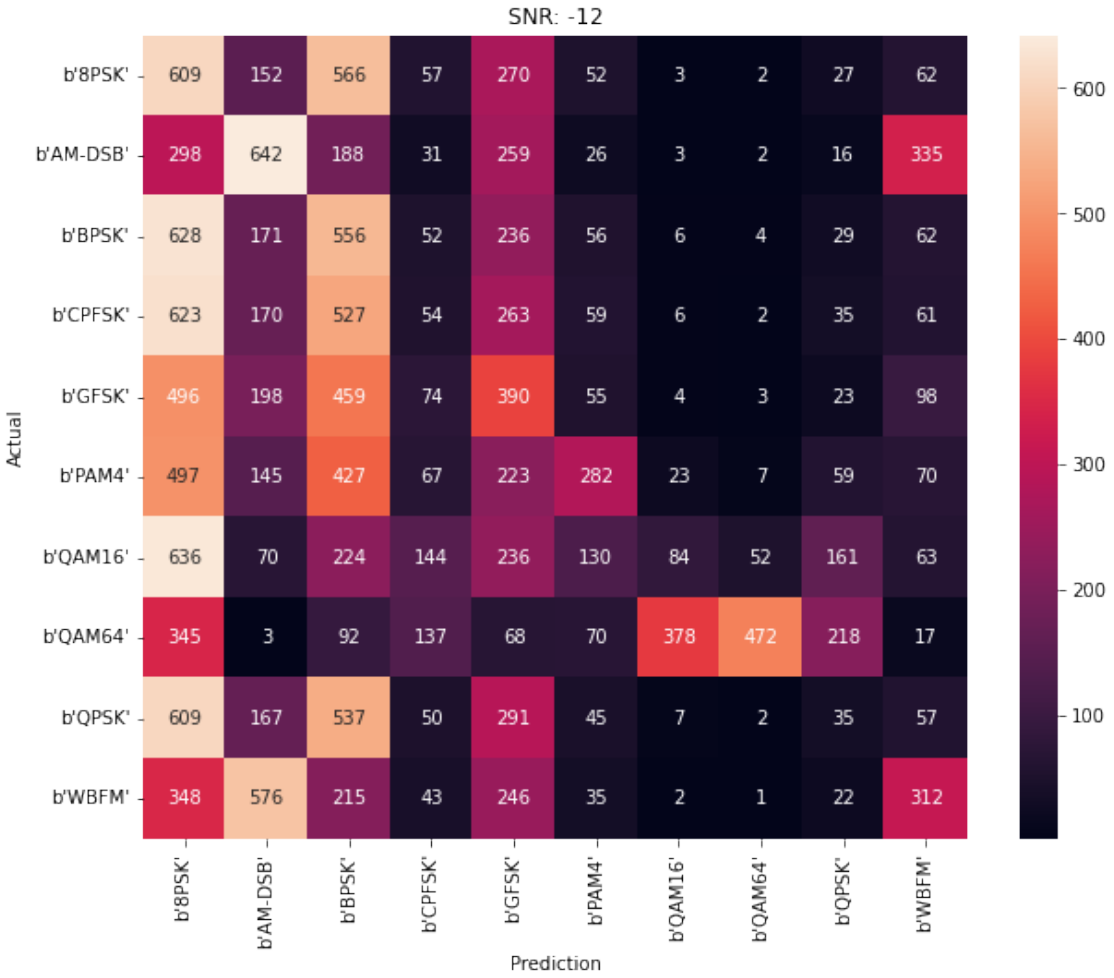

```
Accuracy at SNR = -16 is 0.11811111111111111%
```



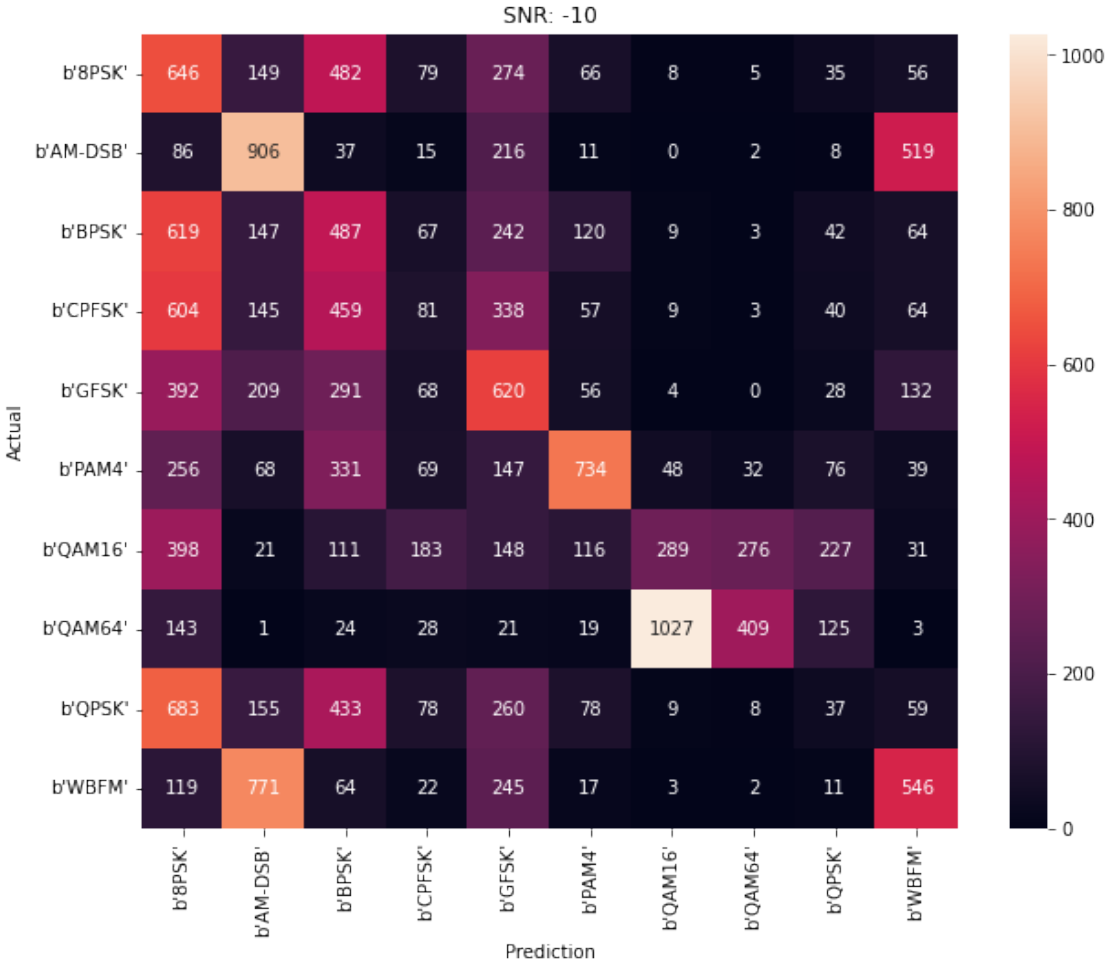

```
Accuracy at SNR = -14 is 0.143%
```



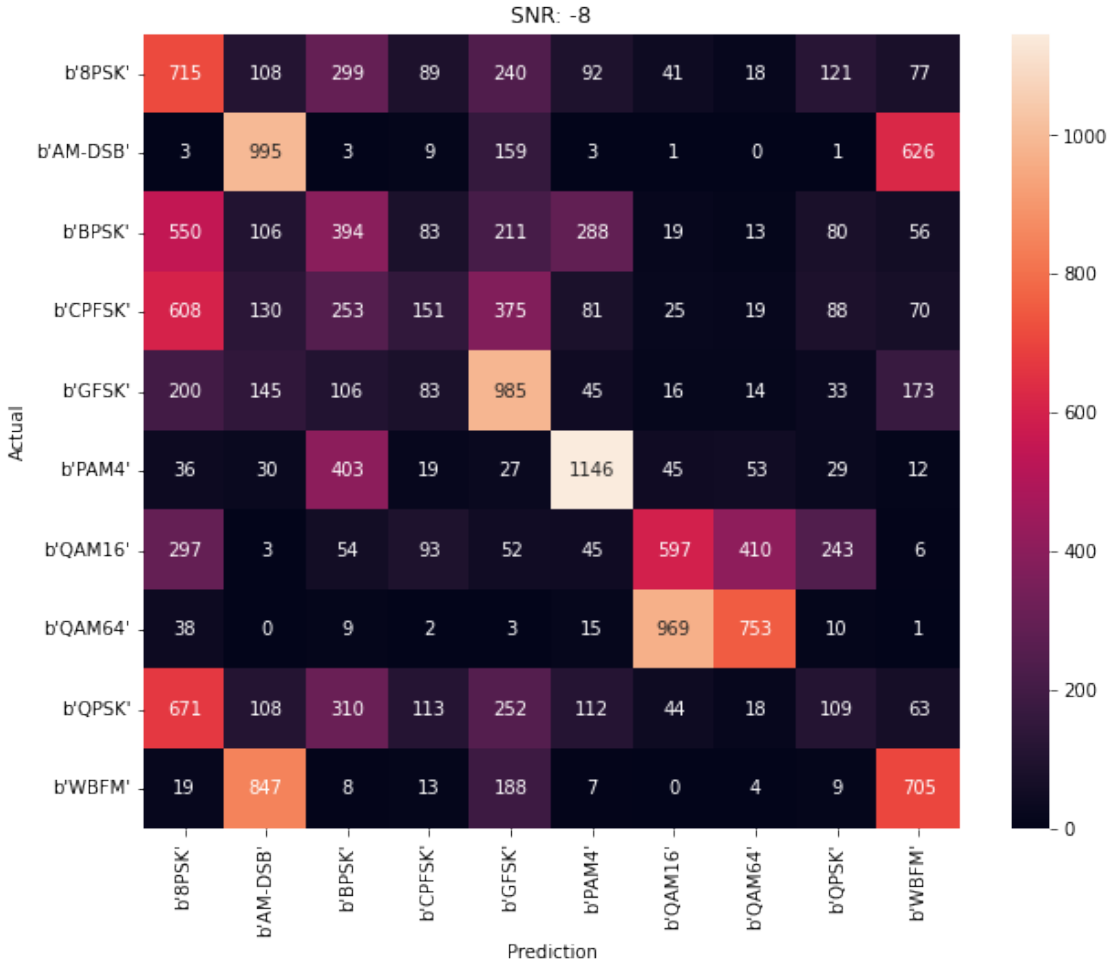

```
Accuracy at SNR = -12 is 0.19088888888888889%
```



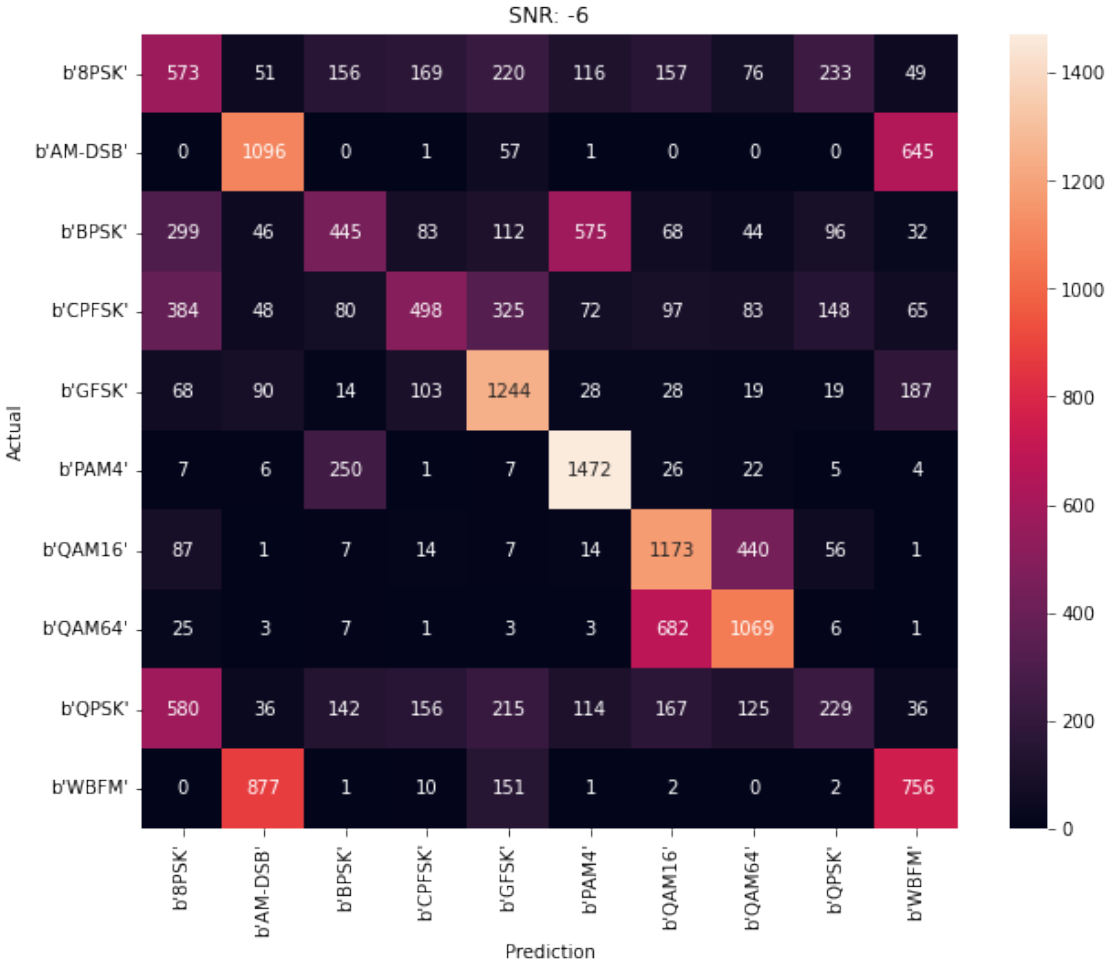

```
Accuracy at SNR = -10 is 0.26416666666666666%
```



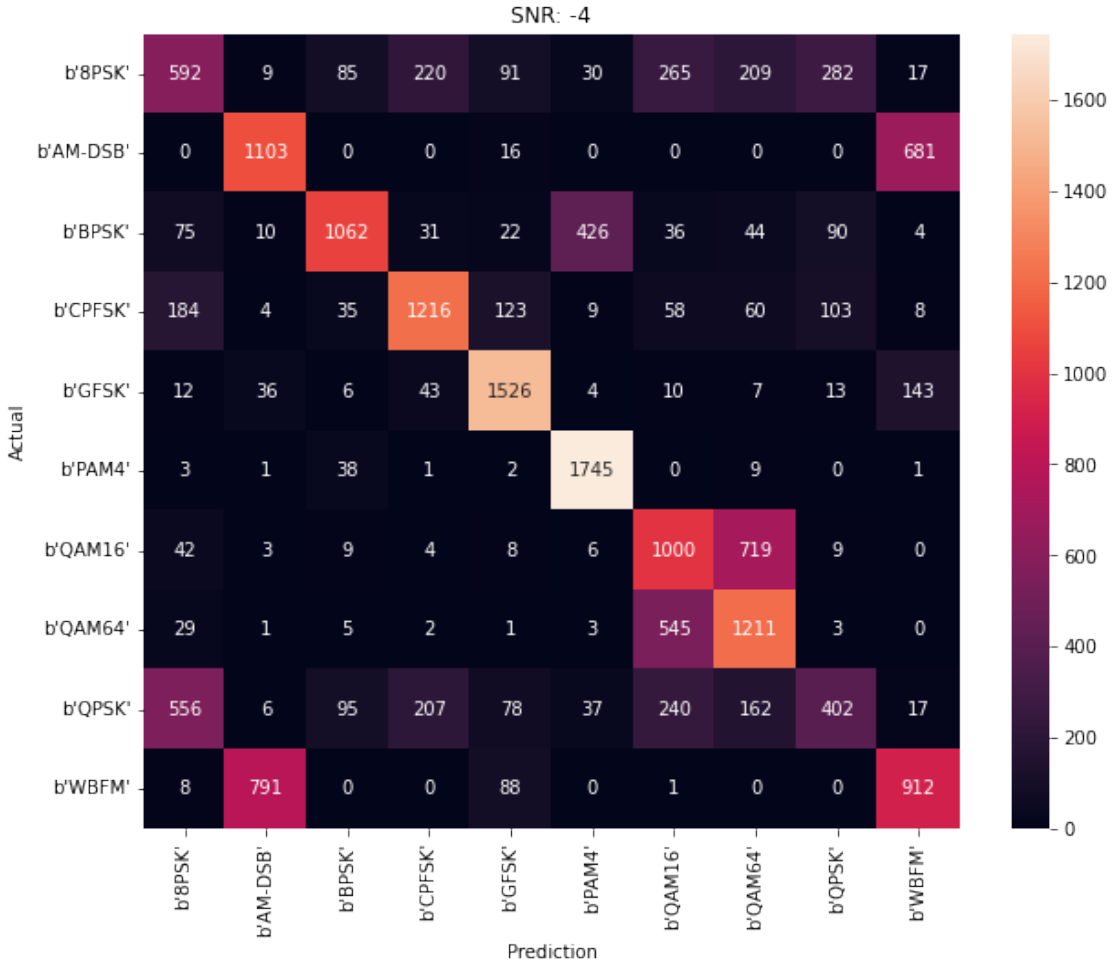

```
Accuracy at SNR = -8 is 0.3638888888888889%
```



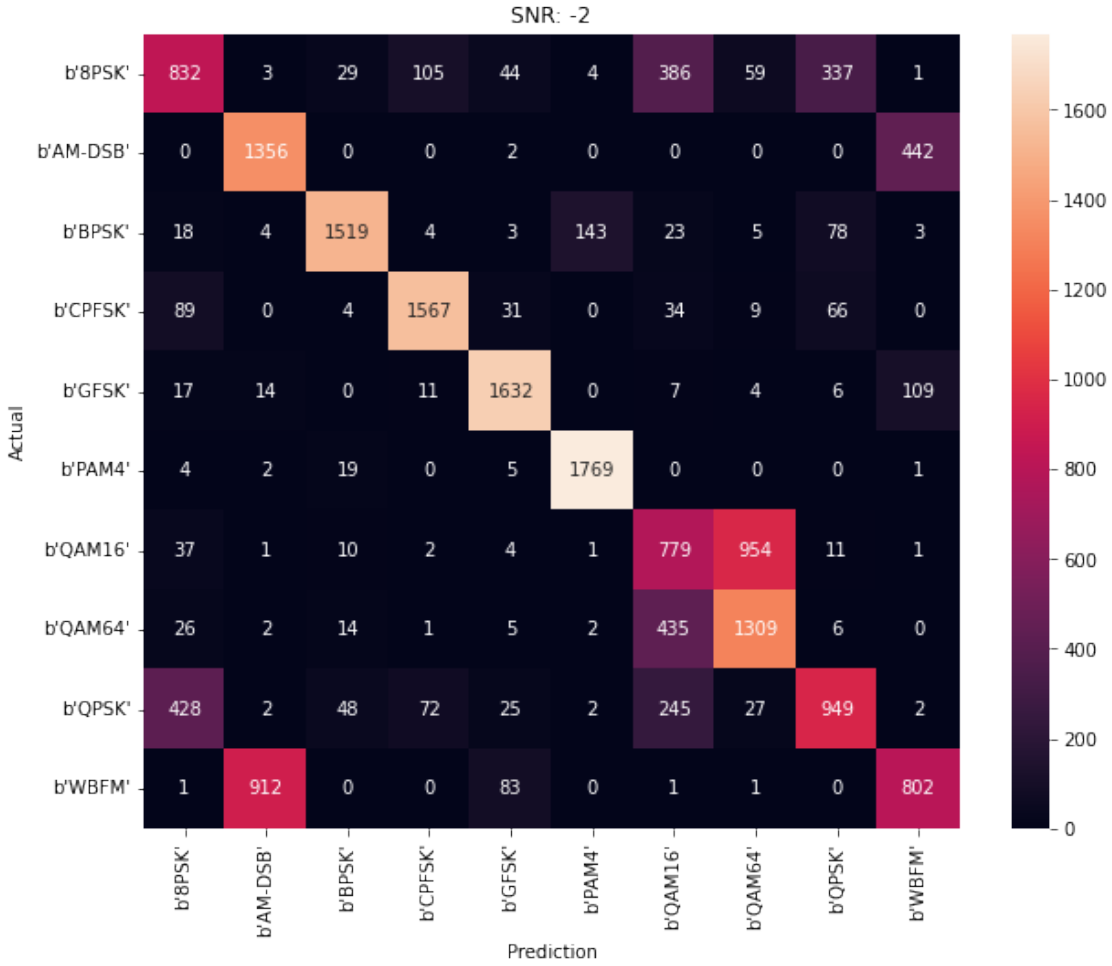
Accuracy at SNR = -6 is 0.4752777777777778%



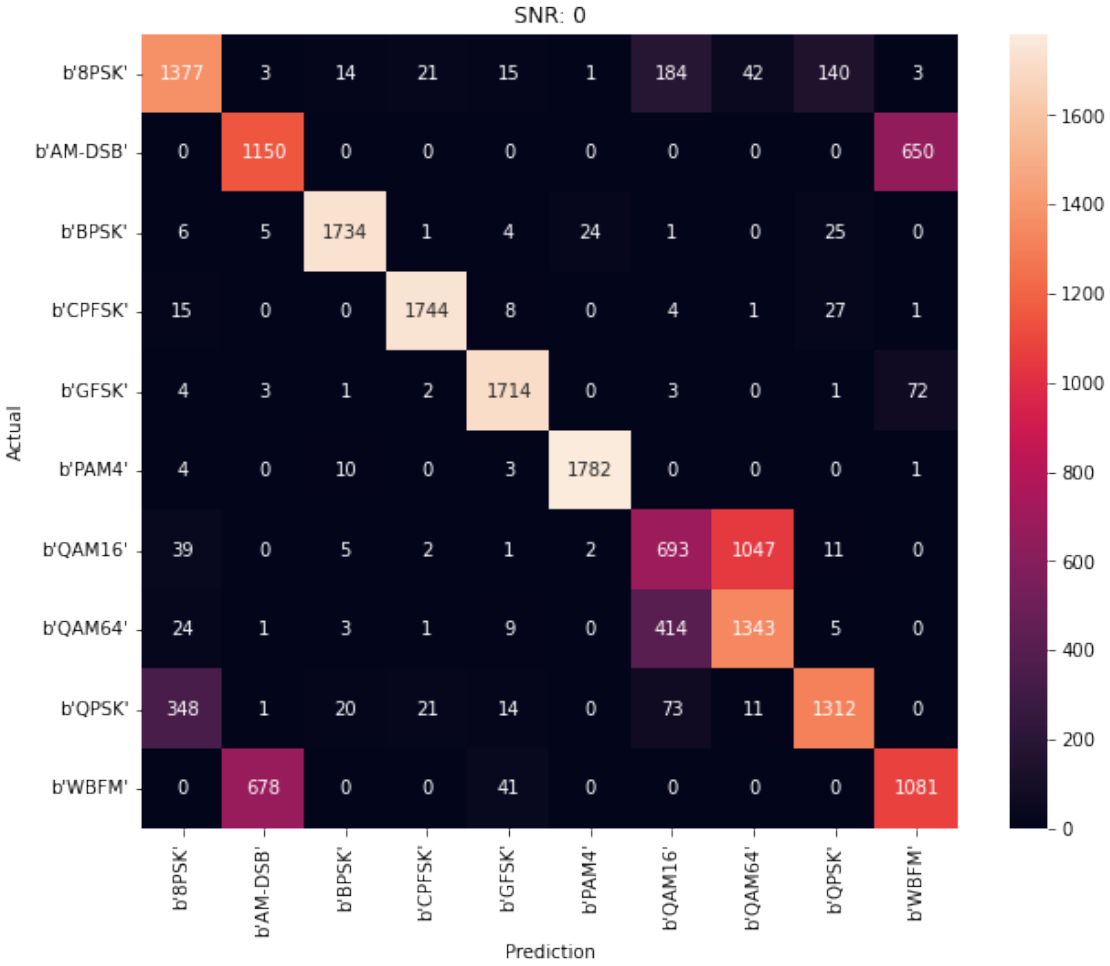

```
Accuracy at SNR = -4 is 0.5982777777777778%
```



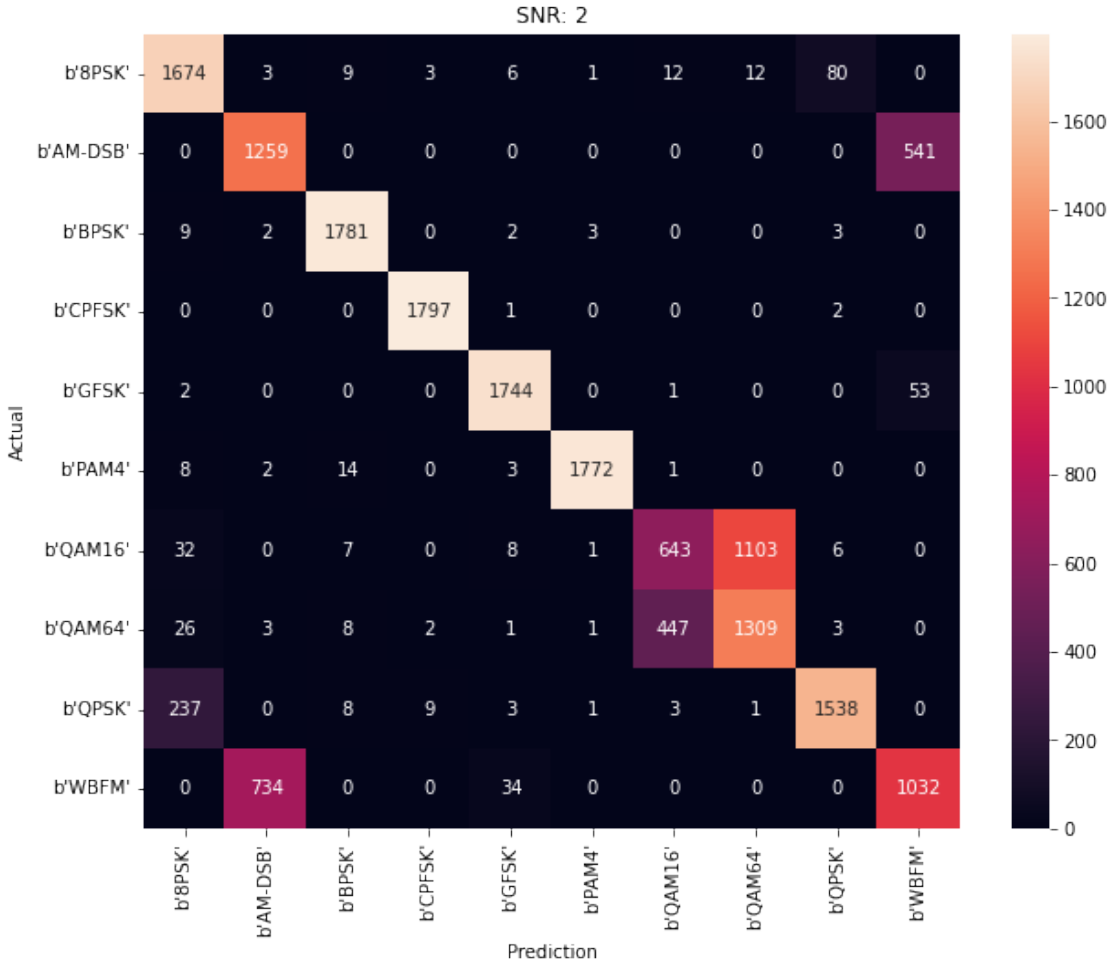

```
Accuracy at SNR = -2 is 0.6952222222222222%
```



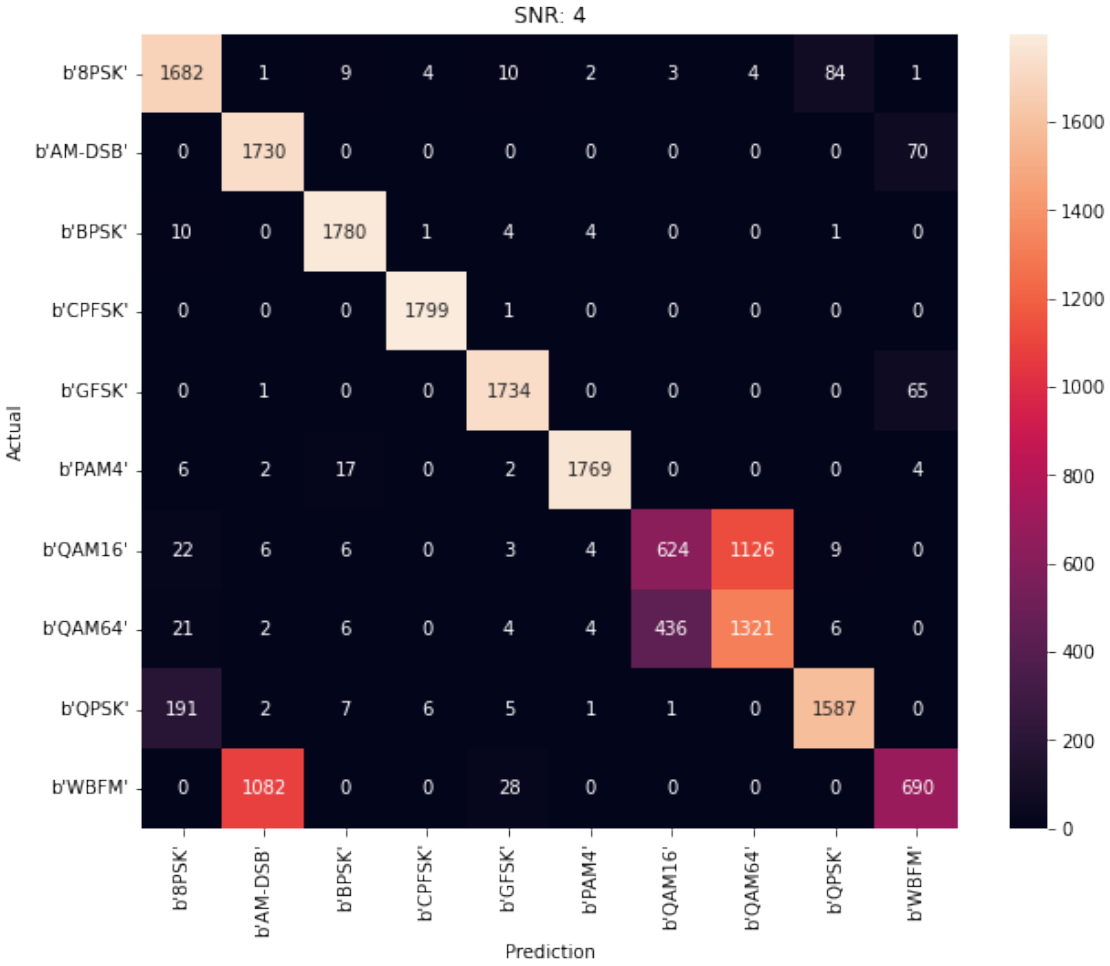

```
Accuracy at SNR = 0 is 0.7738888888888888%
```



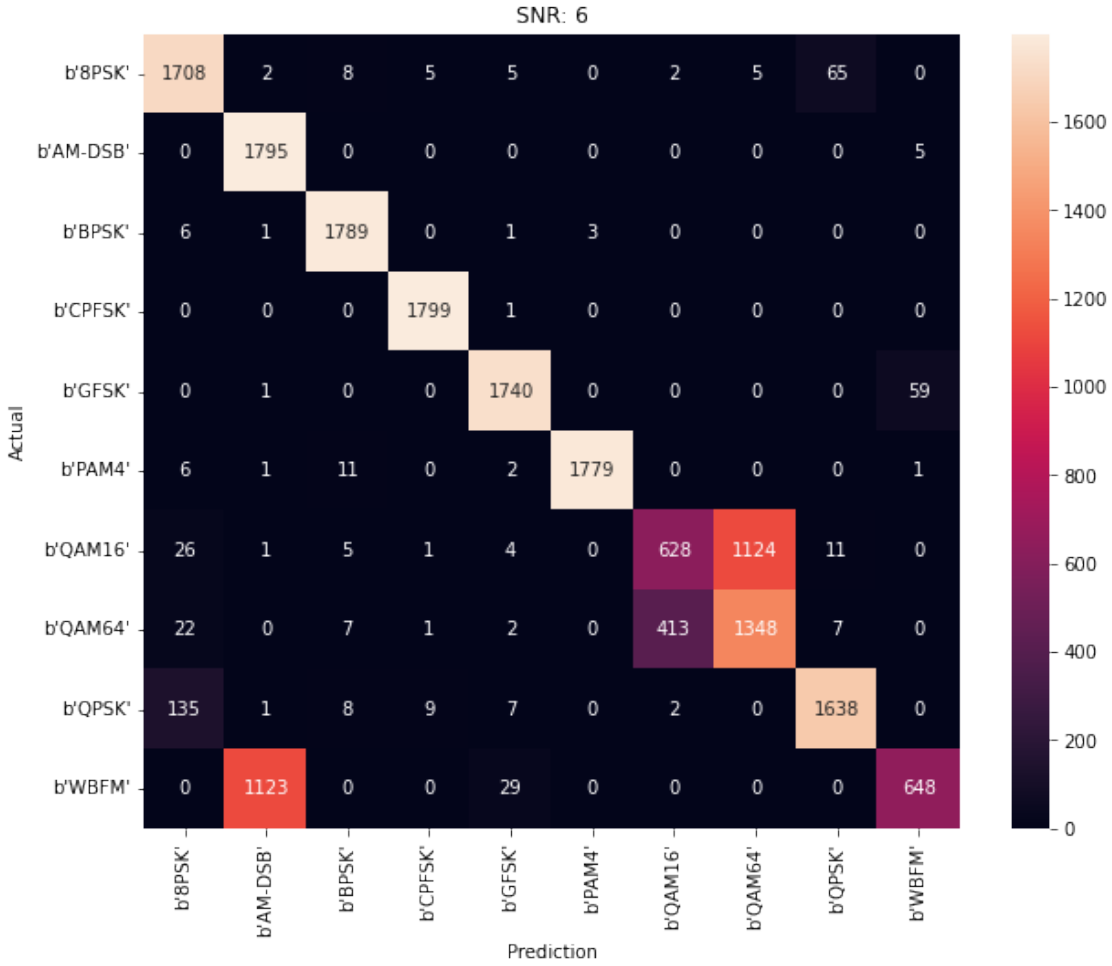

```
Accuracy at SNR = 2 is 0.8082777777777778%
```



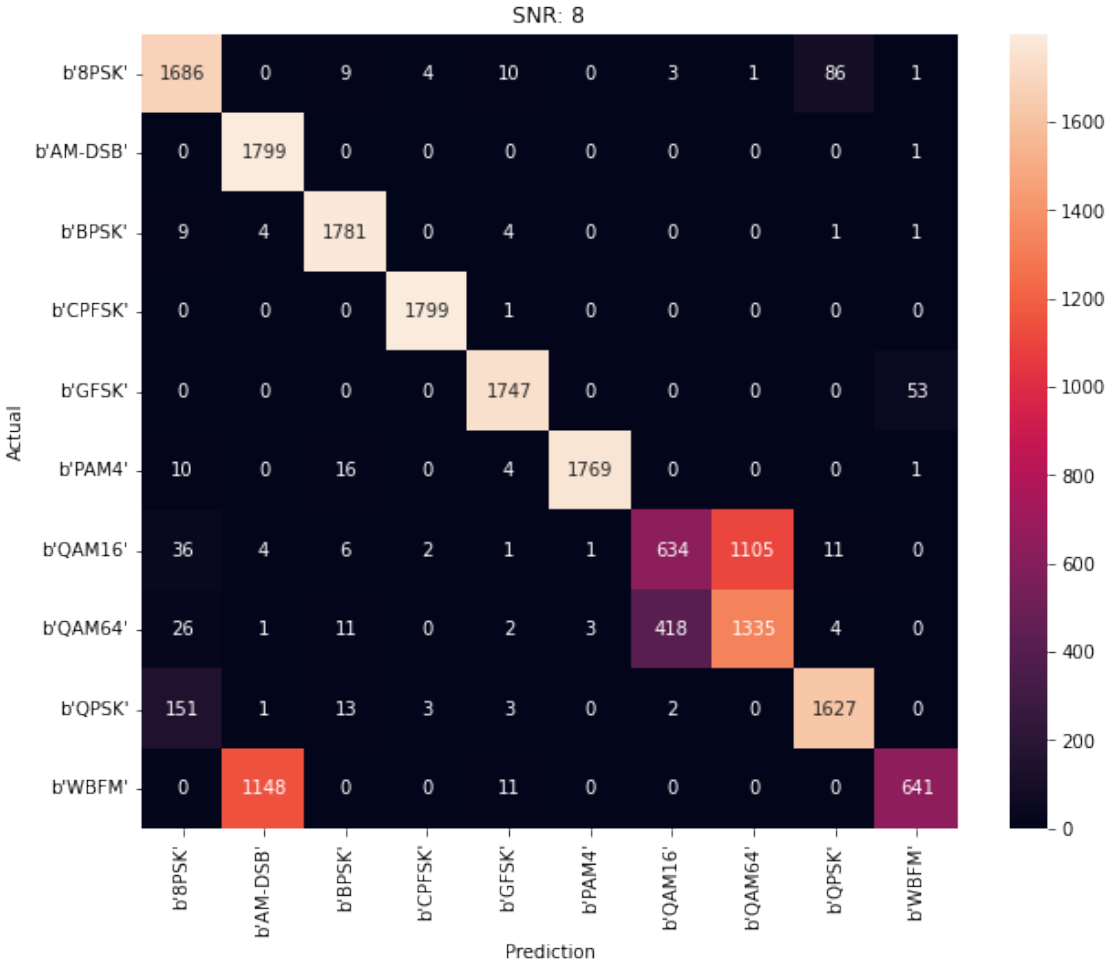

```
Accuracy at SNR = 4 is 0.8175555555555556%
```



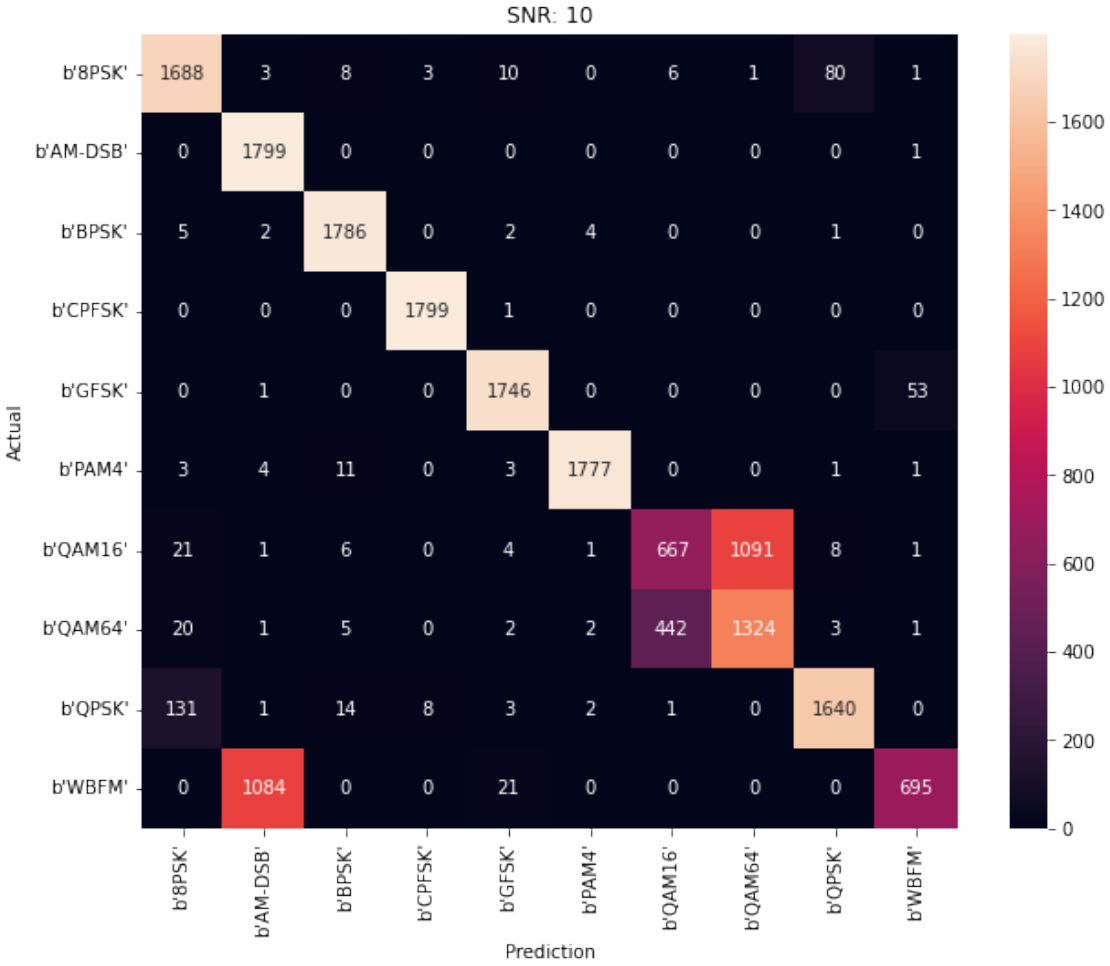

```
Accuracy at SNR = 6 is 0.8262222222222222%
```



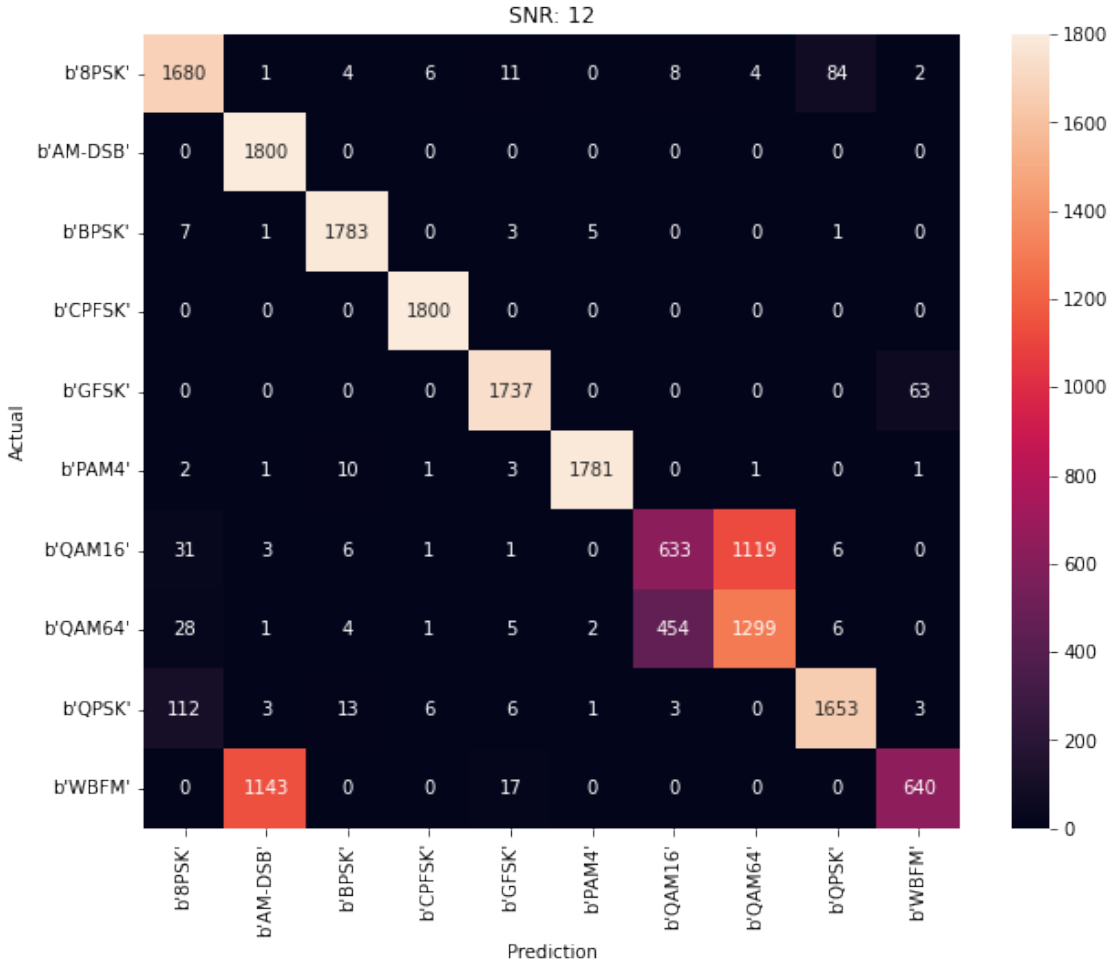

```
Accuracy at SNR = 8 is 0.8232222222222222%
```



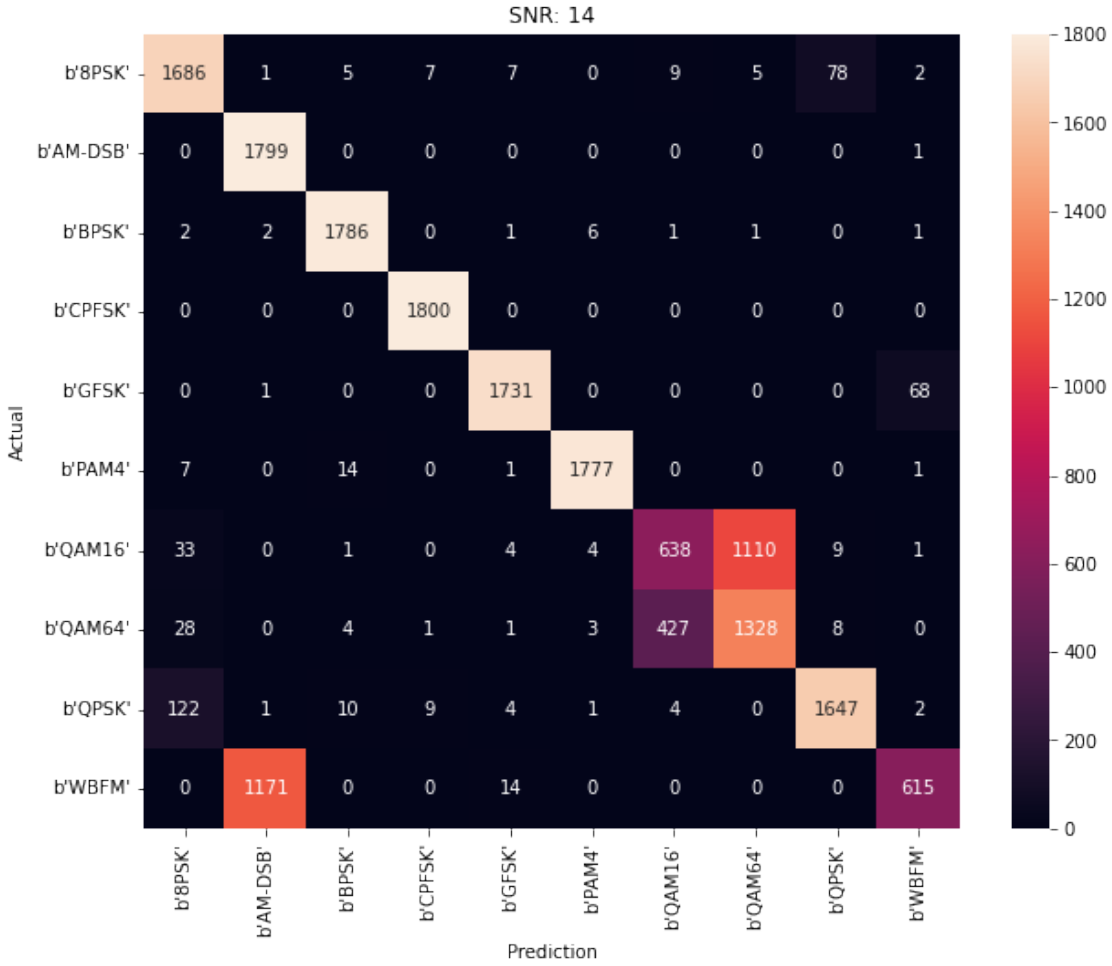

```
Accuracy at SNR = 10 is 0.8289444444444445%
```



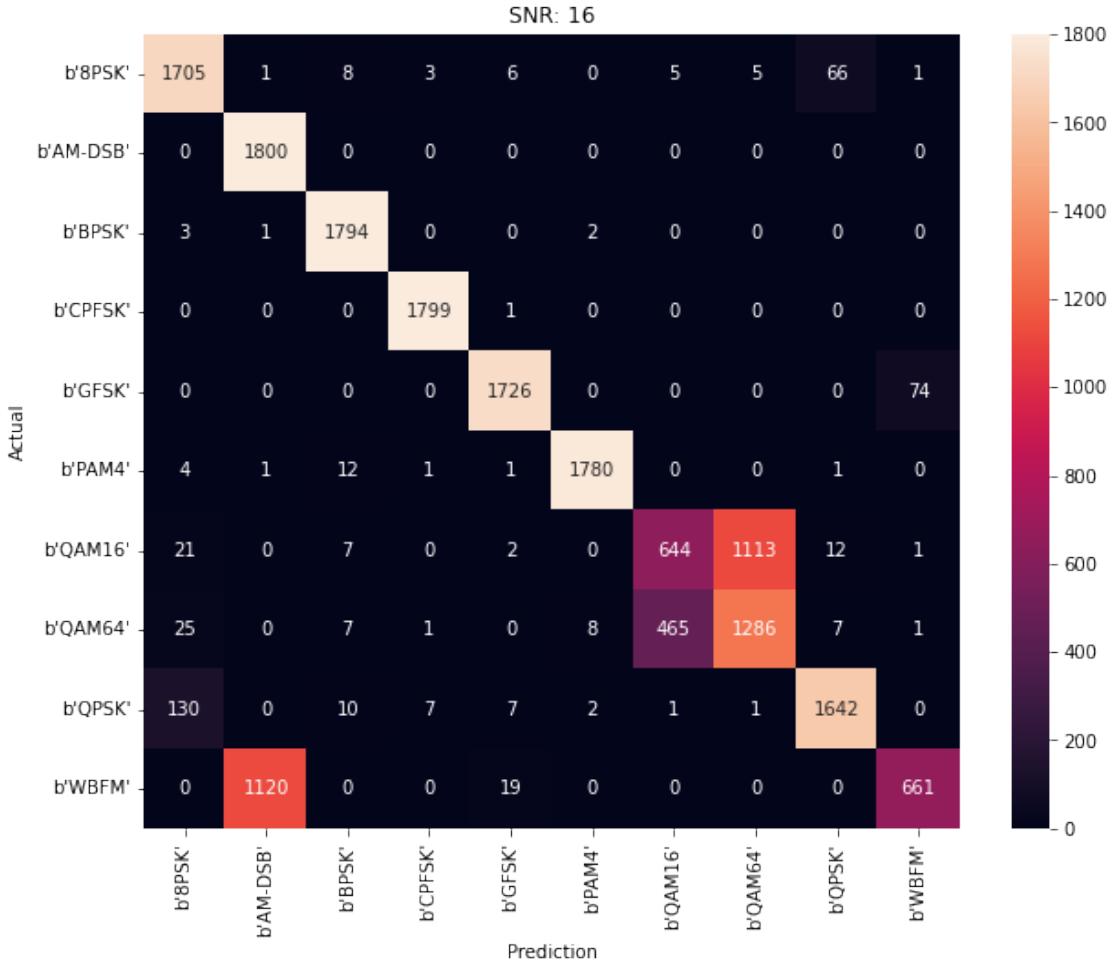
Accuracy at SNR = 12 is 0.8225555555555556%



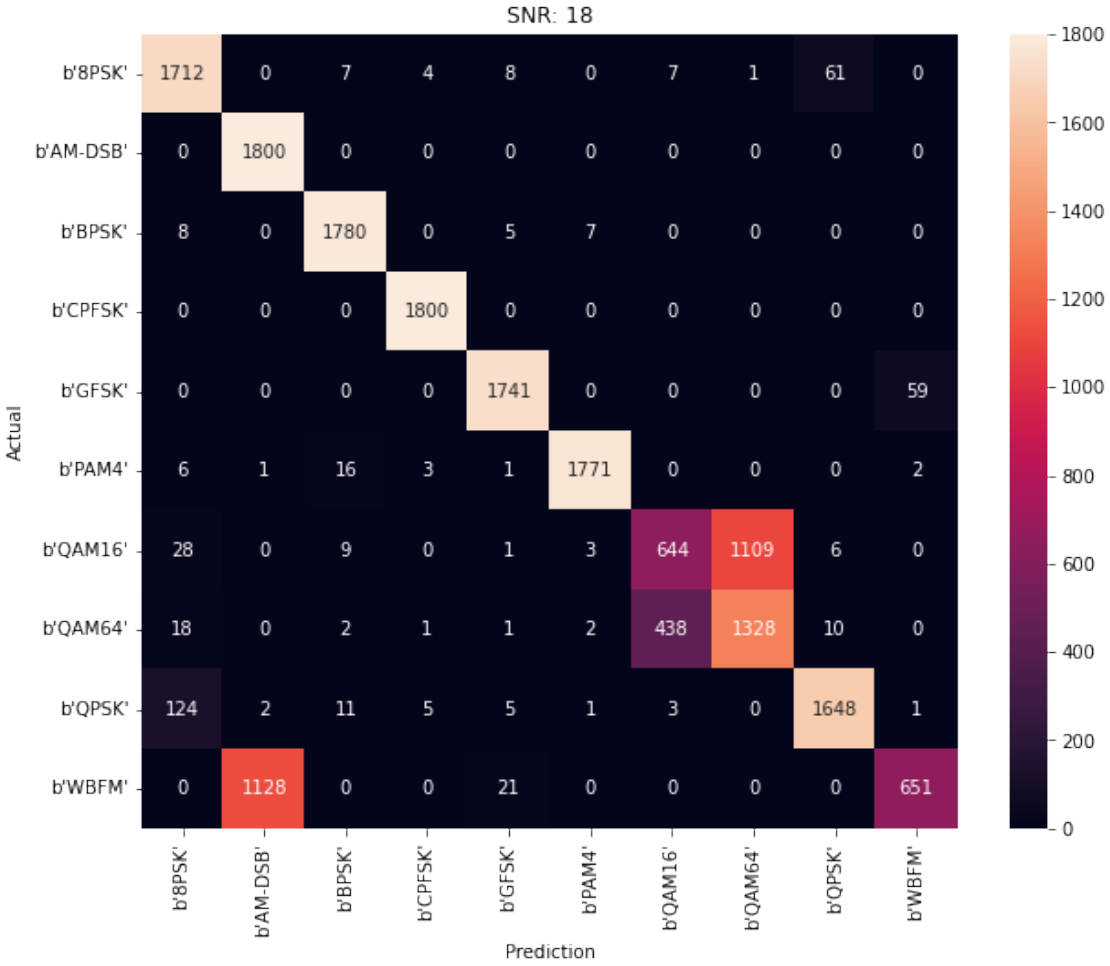
Accuracy at SNR = 14 is 0.8226111111111111%

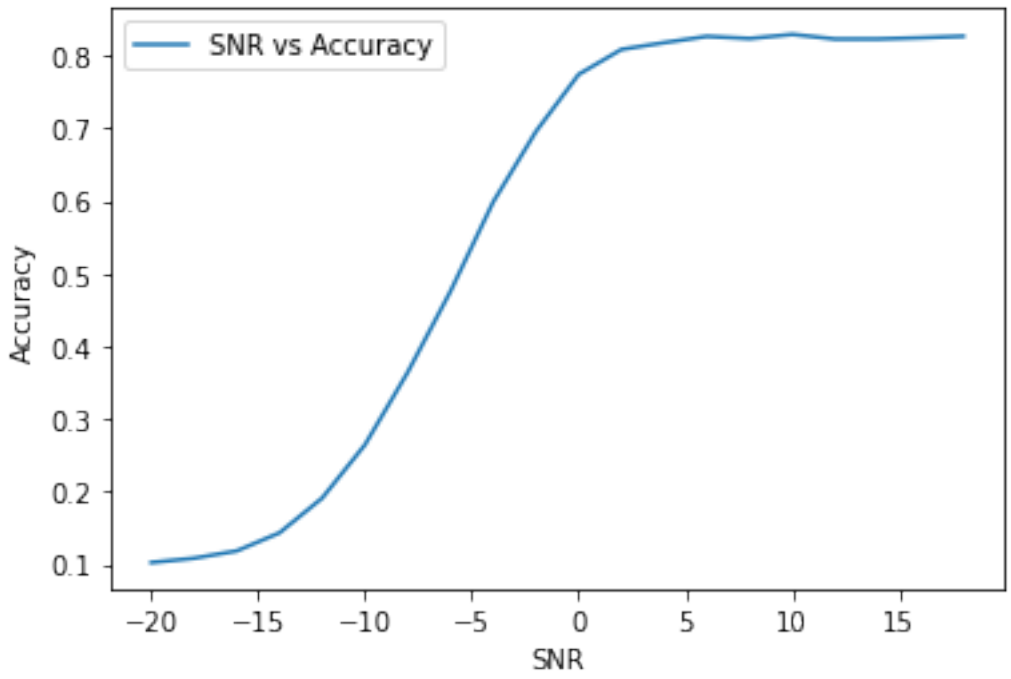



```
Accuracy at SNR = 16 is 0.8242777777777778%
```




```
Accuracy at SNR = 18 is 0.8263888888888888%
```


SNR: 18
b'8PSK' 1712 0 7 4 8 0 7 1 61 0
b'AM-DSB' 0 1800 0 0 0 0 0 0 0 0
b'BPSK' 8 0 1780 0 5 7 0 0 0 0
b'CPFSK' 0 0 0 1800 0 0 0 0 0 0
b'GFSK' 0 0 0 0 1741 0 0 0 0 59
b'PAM4' 6 1 16 3 1 1771 0 0 0 2
b'QAM16' 28 0 9 0 1 3 644 1109 6 0
b'QAM64' 18 0 2 1 1 2 438 1328 10 0
b'QPSK' 124 2 11 5 5 1 3 0 1648 1
b'WBFM' 0 1128 0 0 21 0 0 0 0 651
Actual
b'8PSK' b'AM-DSB' b'BPSK' b'CPFSK' b'GFSK' b'PAM4' b'QAM16' b'QAM64' b'QPSK' b'WBFM'
Prediction
1800 1600 1400 1200 1000 800 600 400 200 0



8.2 Reshaping data for RNN and LSTM models

[31]:
```
fiit_training_data, fiit_validation_data, fiit_testing_data =␣
↪reshape_data_for_rnn_lstm(fiit_training_data, fiit_validation_data,␣
↪fiit_testing_data)
```

[32]:
```
print('training data shape:', fiit_training_data.shape)
print('validation data shape:', fiit_validation_data.shape)
print('testing data shape:', fiit_testing_data.shape)
```

```
training data shape: (798000, 2, 128)
validation data shape: (42000, 2, 128)
testing data shape: (360000, 2, 128)
```

8.3 RNN Model

[33]:
```
learning_rate = 0.001
batch_size = 512
epochs = 200
```

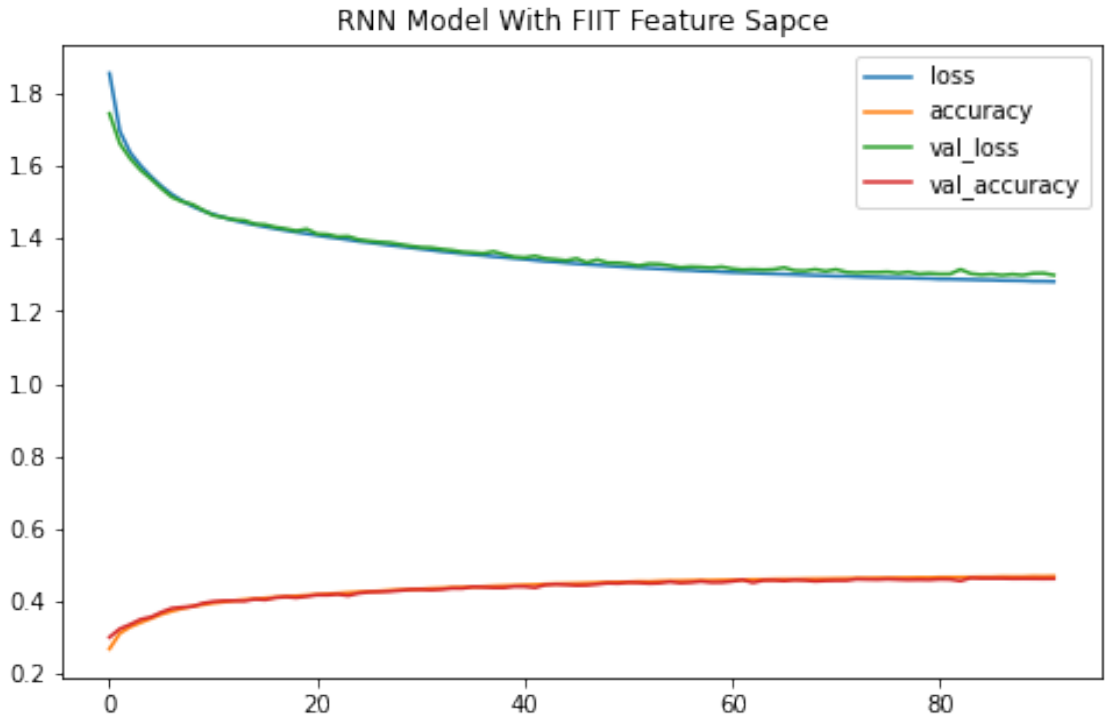
[34]:
```
rnn_model = Sequential()
rnn_model.add(SimpleRNN(128, activation='relu'))
#rnn_model.add(Dropout(0.5))
rnn_model.add(Dense(10, activation='softmax'))
```

```
rnn_model.compile(loss=tf.keras.losses.CategoricalCrossentropy(),␣
 ↪metrics='accuracy', optimizer=tf.keras.optimizers.
 ↪Adam(learning_rate=learning_rate))
```

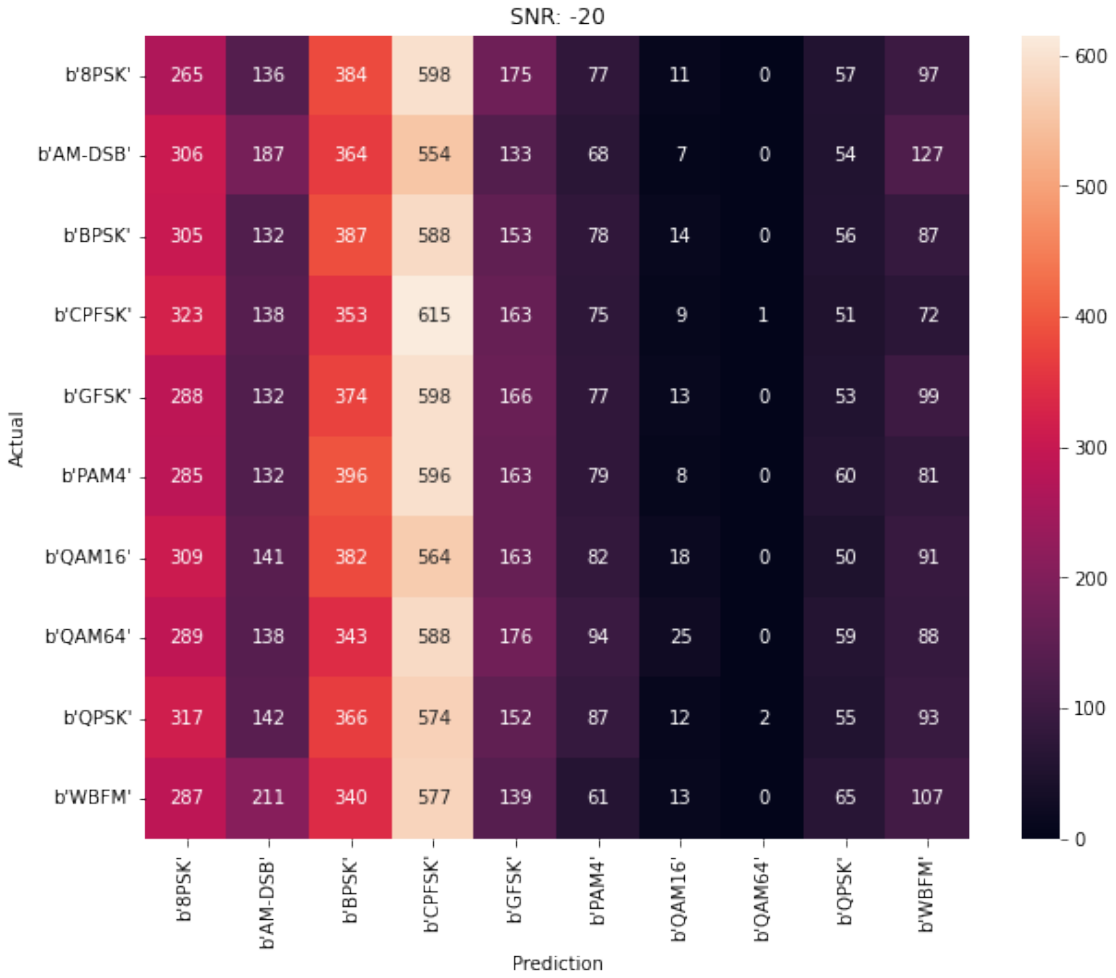
[39]:
```
es = tf.keras.callbacks.EarlyStopping(monitor="val_loss", patience=5,␣
 ↪restore_best_weights=True,)
checkpointer = ModelCheckpoint(filepath='saved_models/rnn_fiit_classification.
 ↪hdf5', verbose=1, save_best_only=True)

with tf.device('/device:GPU:0'):
  history = rnn_model.fit(fiit_training_data, training_onehot,␣
 ↪batch_size=batch_size, epochs=epochs, validation_data=(fiit_validation_data,␣
 ↪validation_onehot), callbacks=[es, checkpointer], verbose=1)
```

```
Epoch 1/200
1555/1559 [============================>.] - ETA: 0s - loss: 1.8557 - accuracy:
0.2679
Epoch 1: val_loss improved from inf to 1.74447, saving model to
saved_models/rnn_fiit_classification.hdf5
1559/1559 [==============================] - 9s 5ms/step - loss: 1.8555 -
accuracy: 0.2680 - val_loss: 1.7445 - val_accuracy: 0.3001

Epoch 92: val_loss did not improve from 1.29858
1559/1559 [==============================] - 8s 5ms/step - loss: 1.2812 -
accuracy: 0.4683 - val_loss: 1.2989 - val_accuracy: 0.4616
```

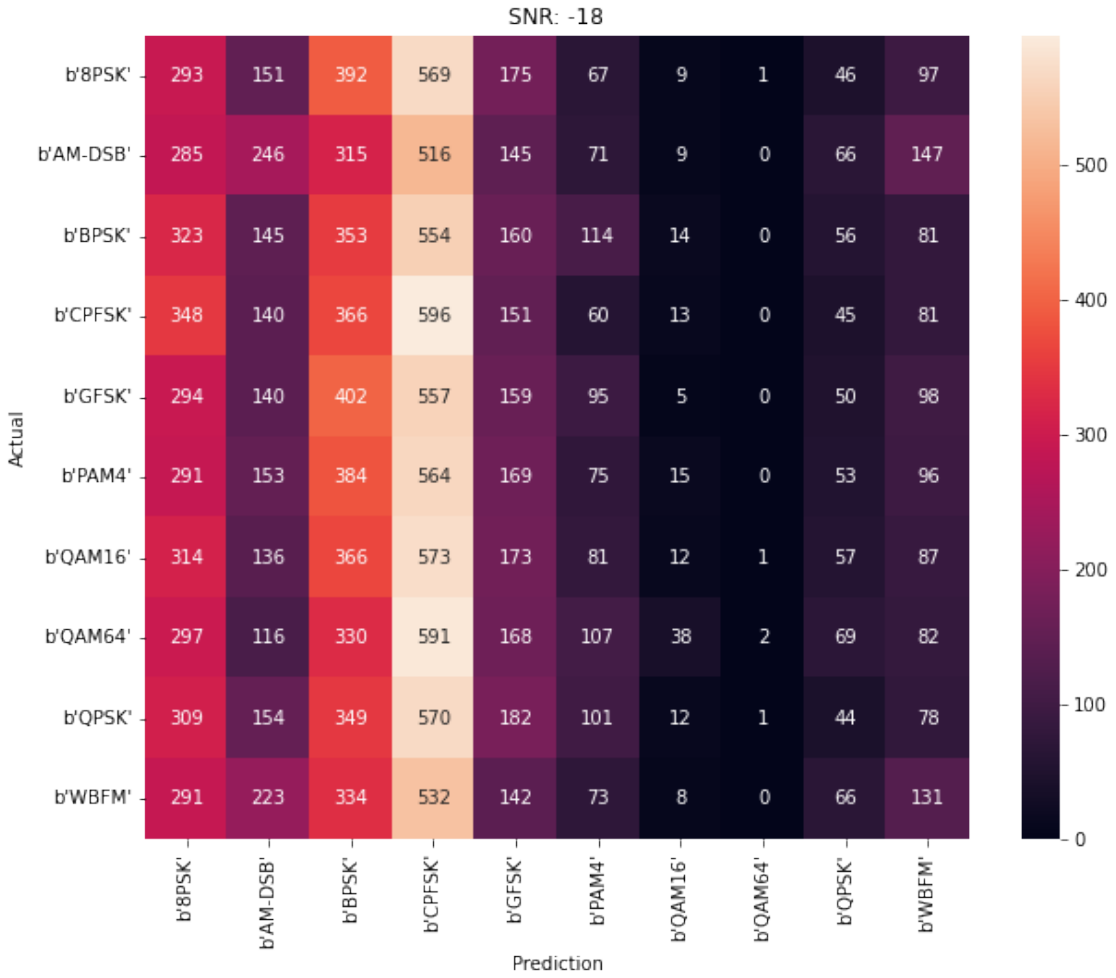
[40]:
```
plot_model_history(history, 'RNN Model With FIIT Feature Sapce')
model_scoring(rnn_model, history, fiit_testing_data, testing_pair_labels)
```



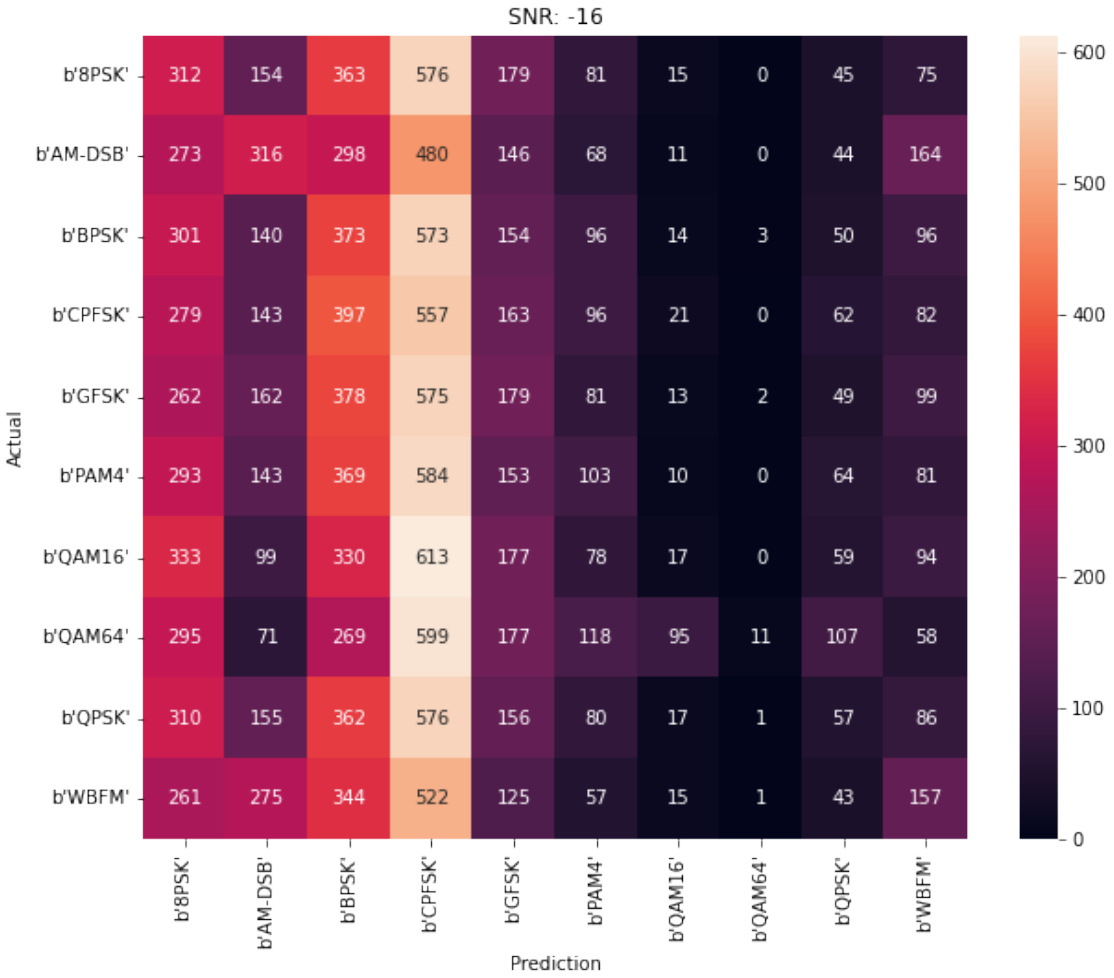

```
Accuracy at SNR = -20 is 0.10438888888888889%
```



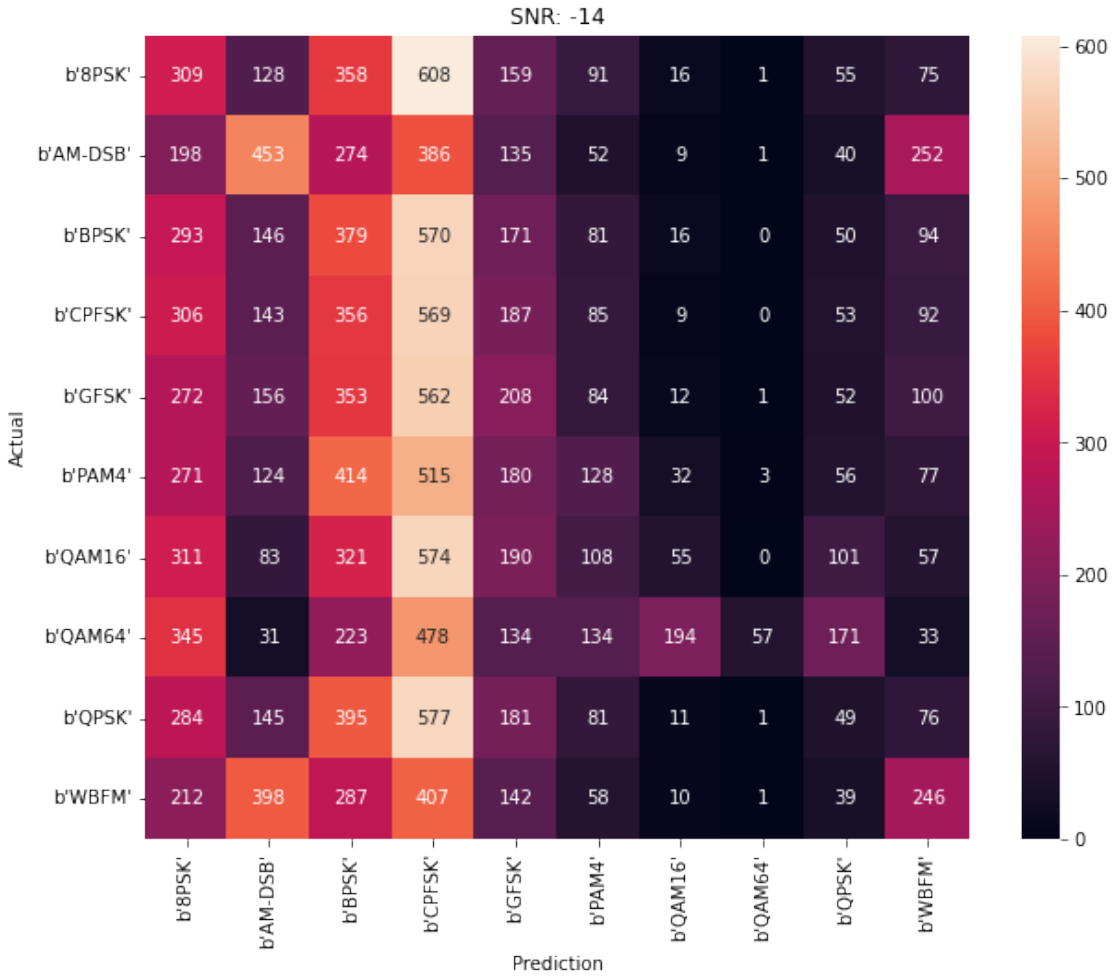

```
Accuracy at SNR = -18 is 0.10616666666666667%
```



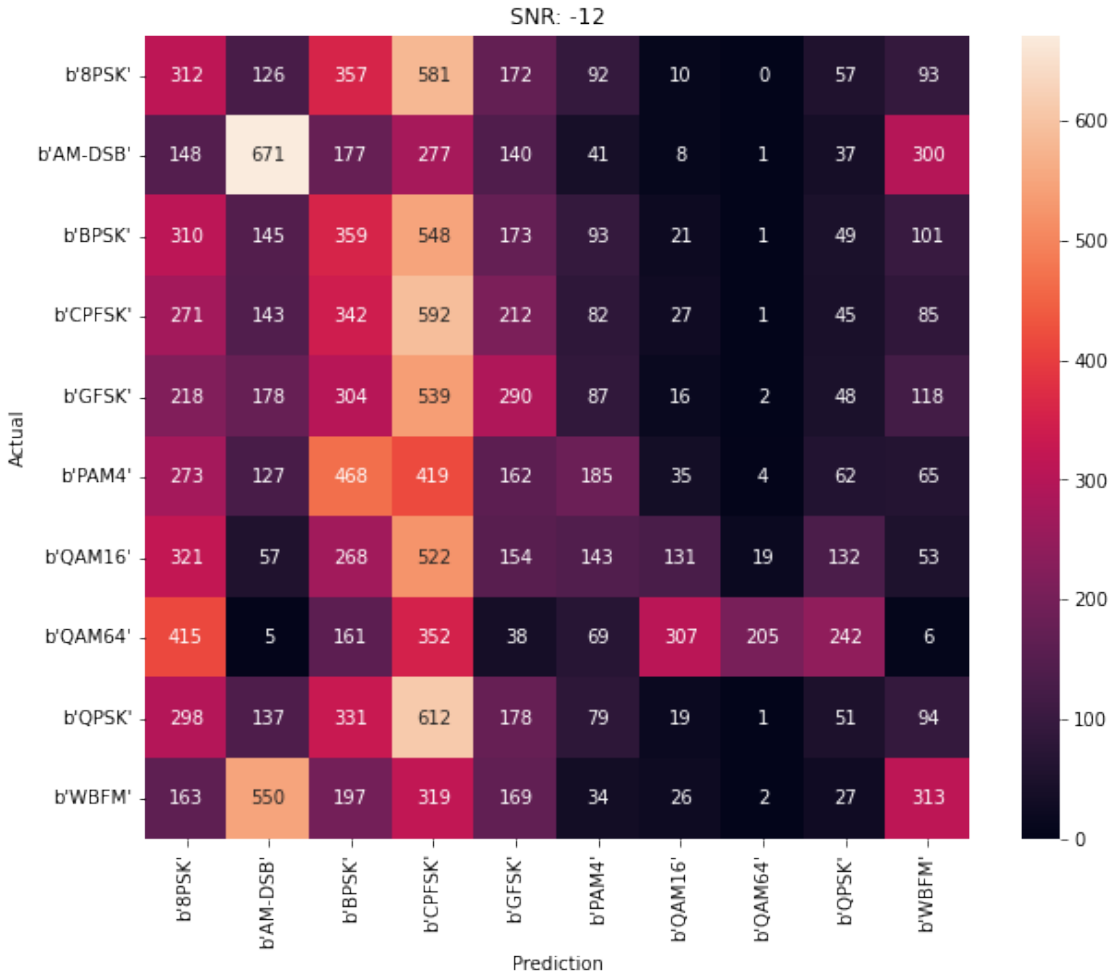

```
Accuracy at SNR = -16 is 0.11566666666666667%
```



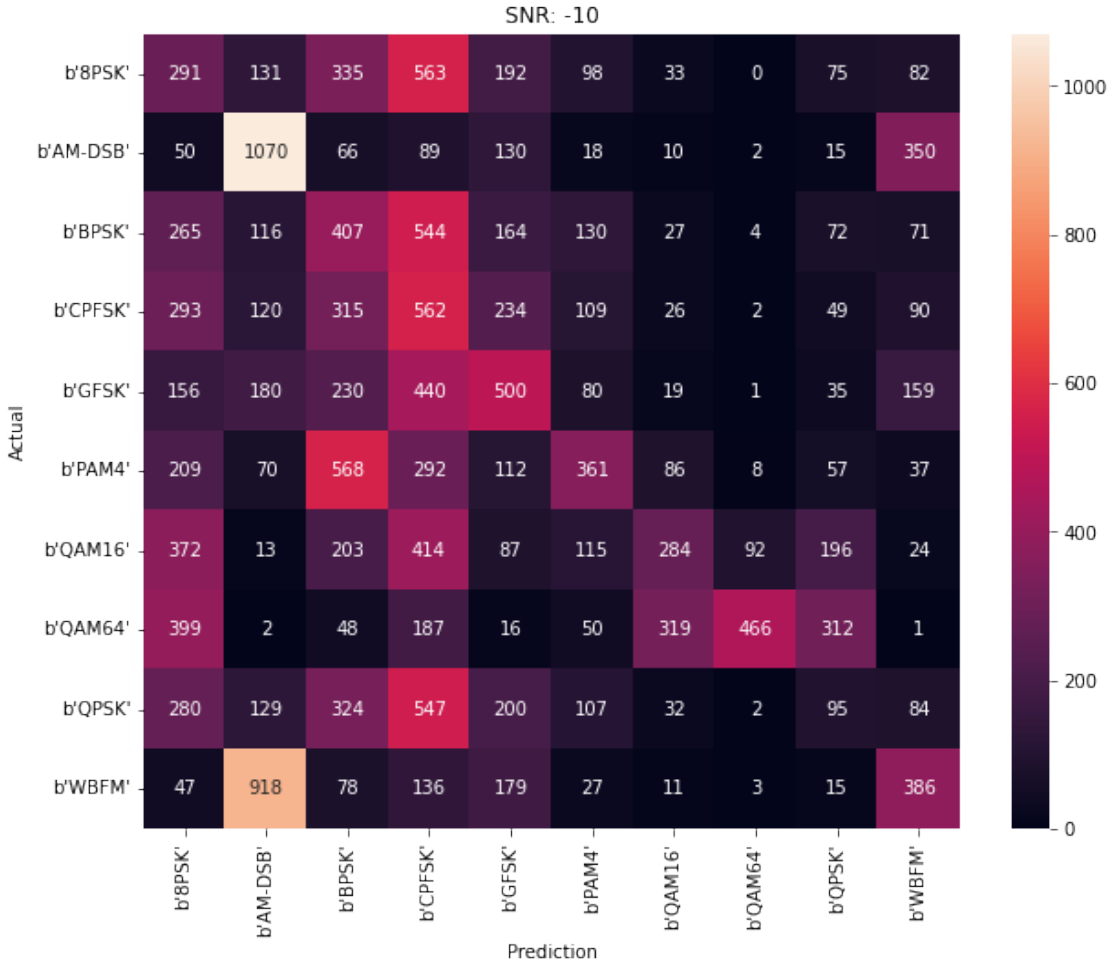

```
Accuracy at SNR = -14 is 0.13627777777777778%
```



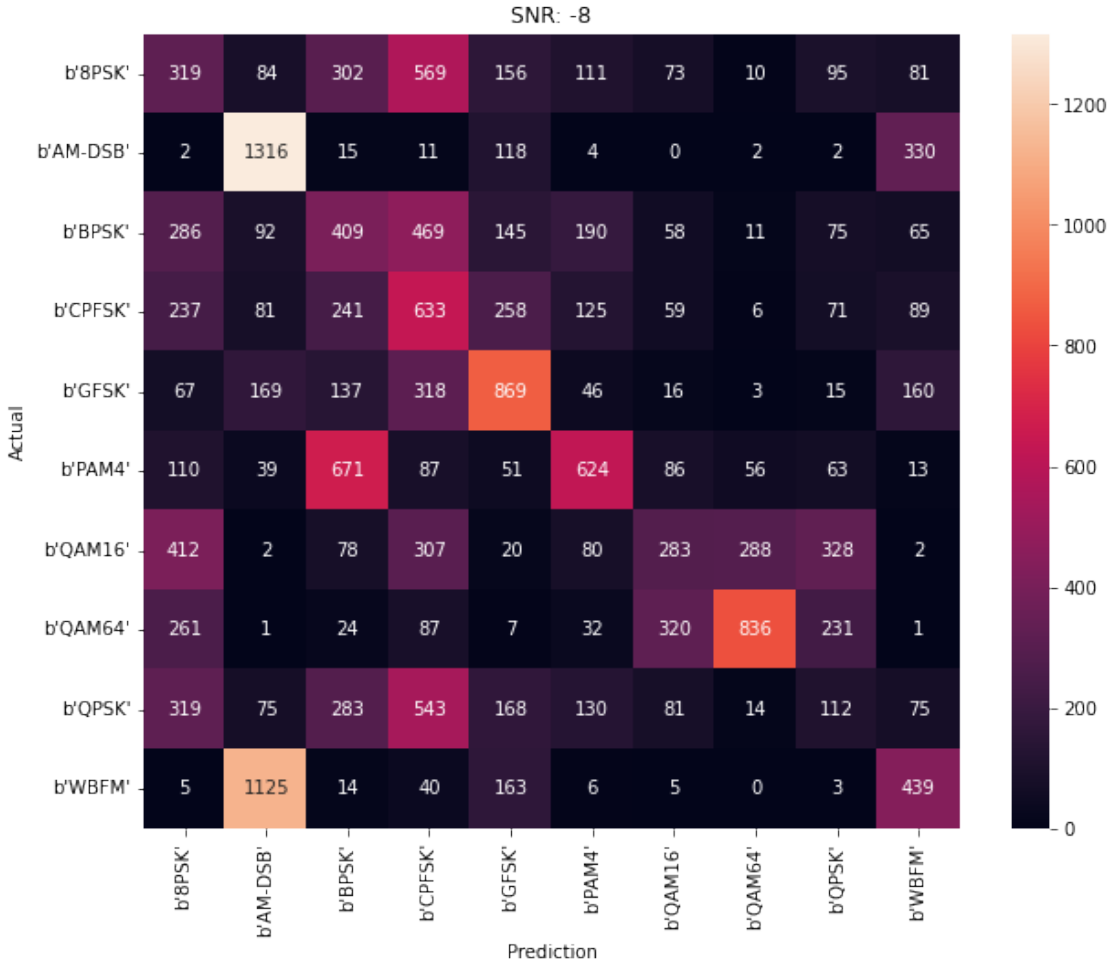

```
Accuracy at SNR = -12 is 0.17272222222222222%
```



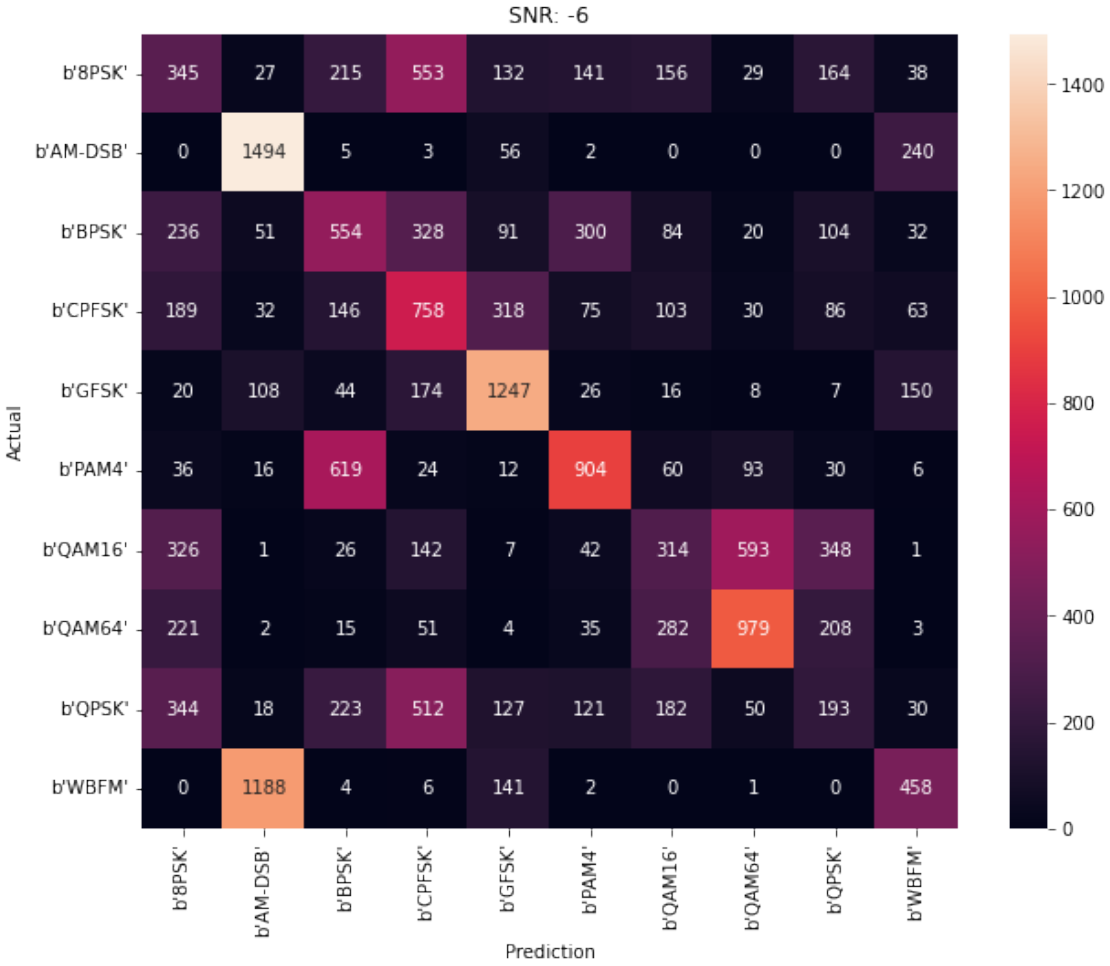

```
Accuracy at SNR = -10 is 0.24566666666666667%
```



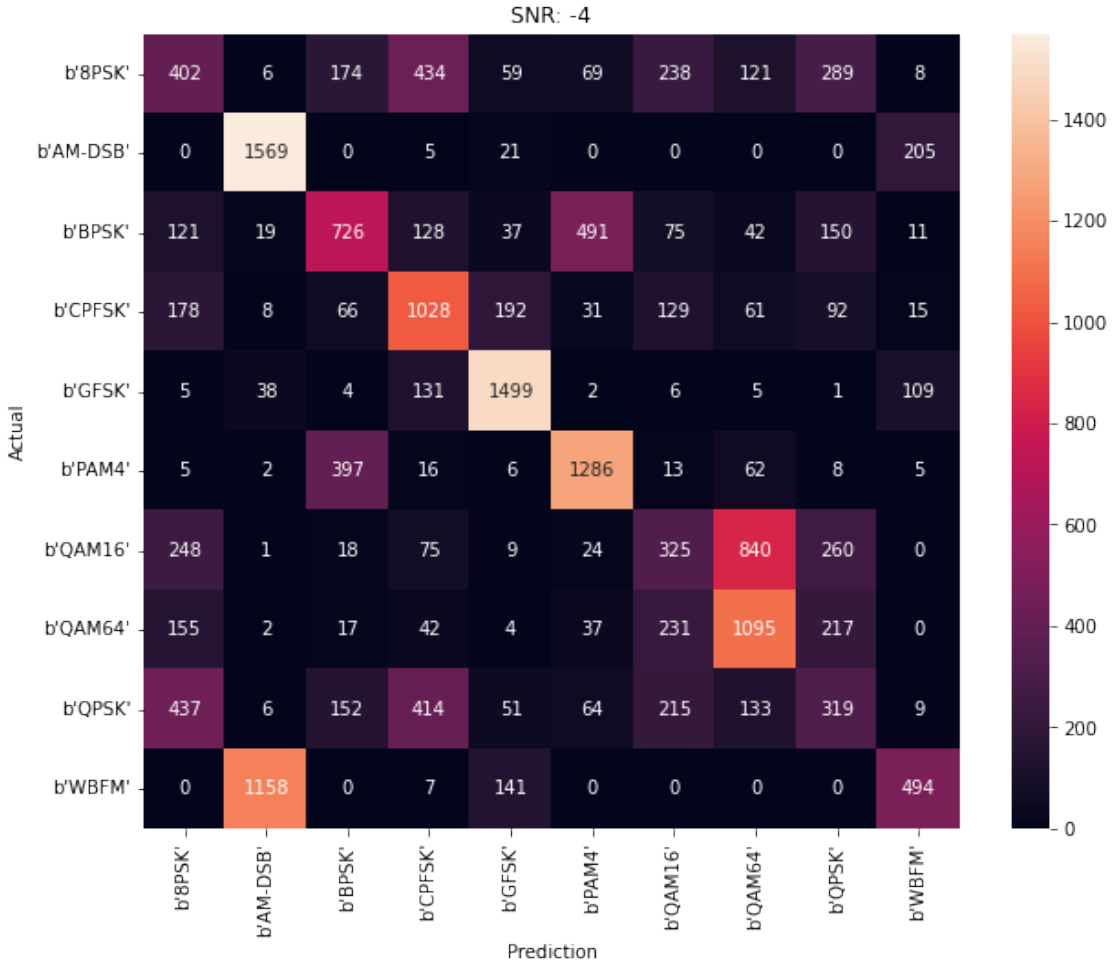

```
Accuracy at SNR = -8 is 0.3244444444444444%
```



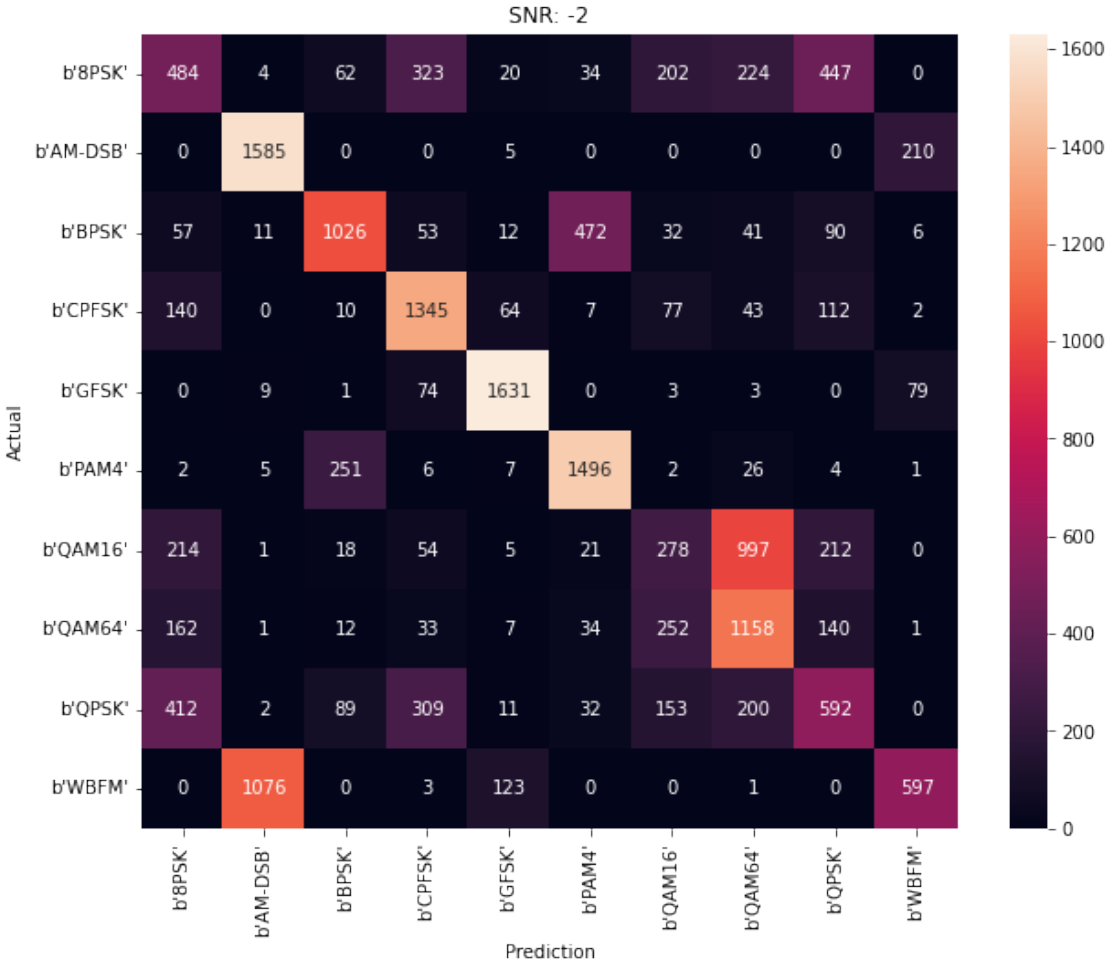
Accuracy at SNR = -6 is 0.40255555555555556%



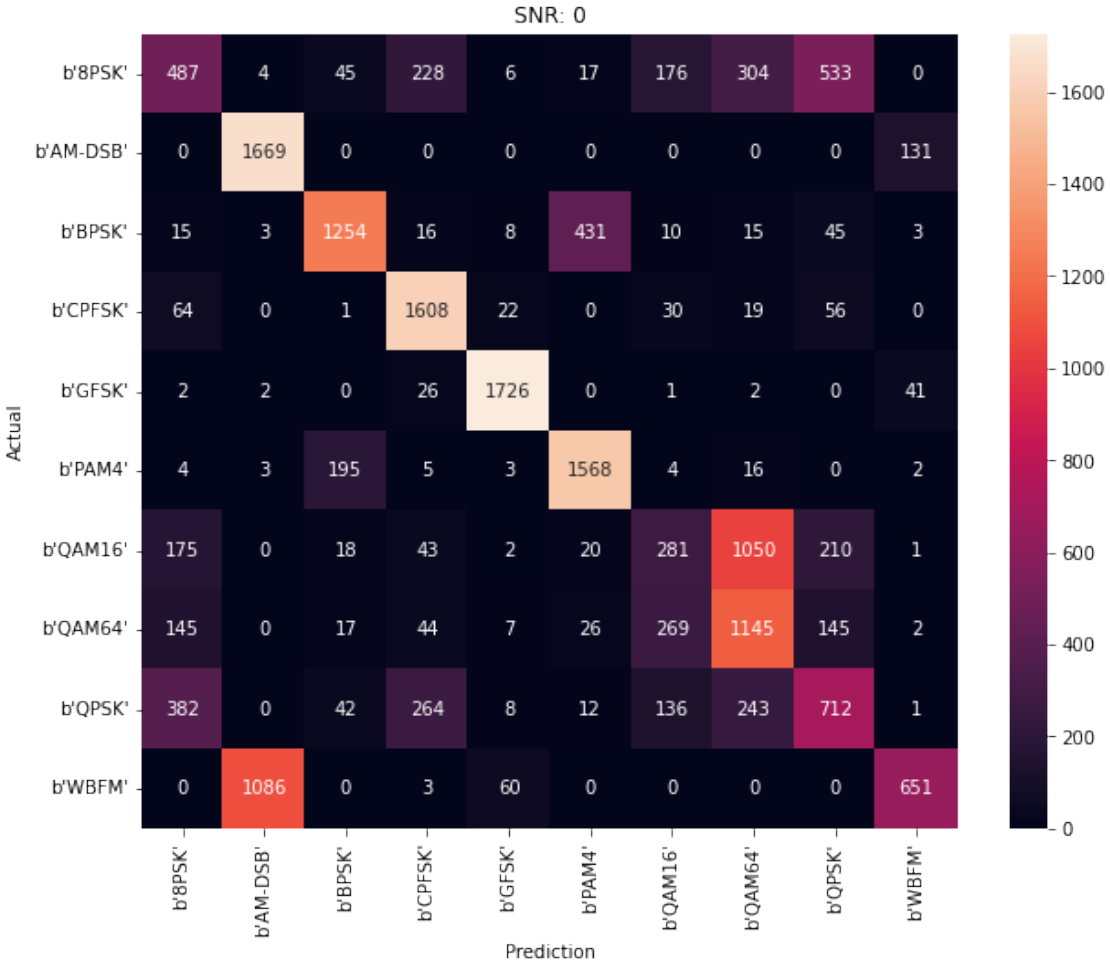

```
Accuracy at SNR = -4 is 0.4857222222222222%
```



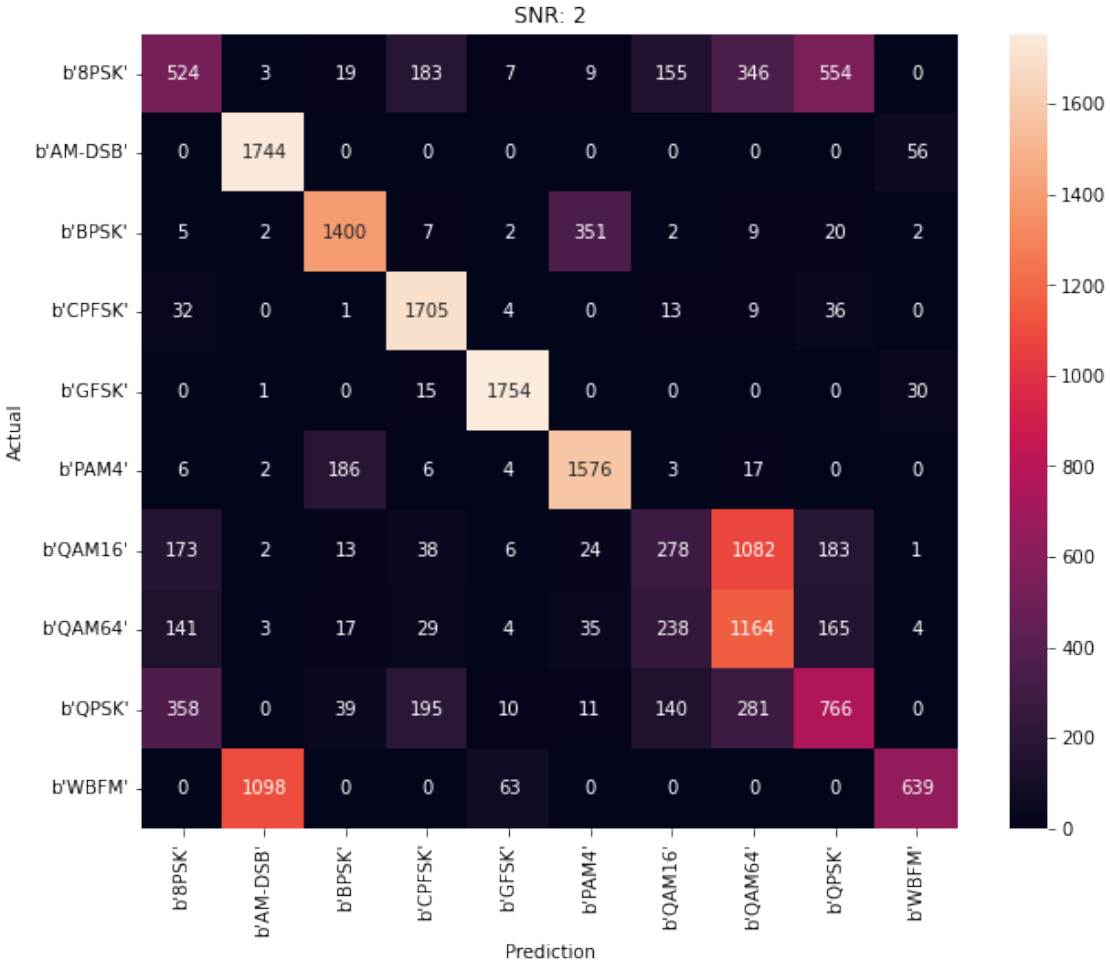

```
Accuracy at SNR = -2 is 0.5662222222222222%
```



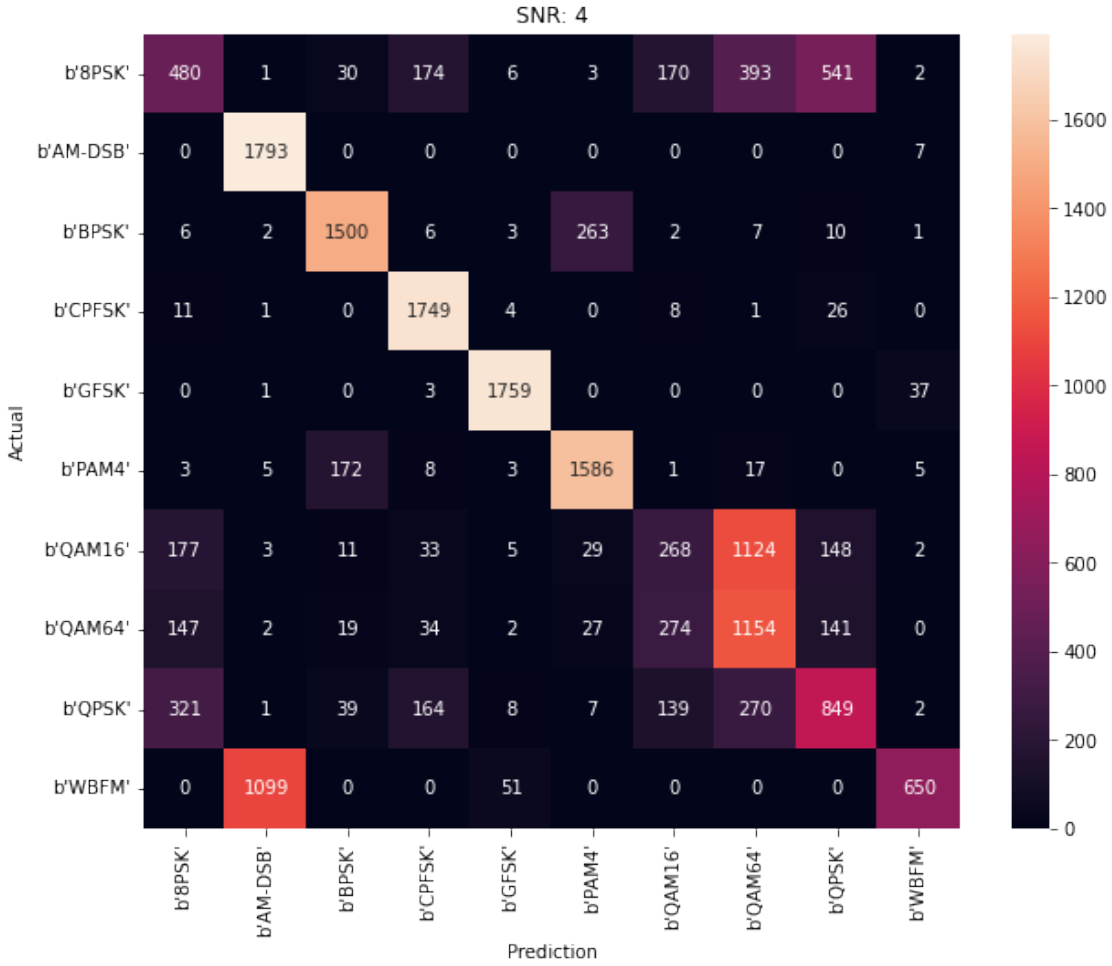

```
Accuracy at SNR = 0 is 0.6167222222222222%
```



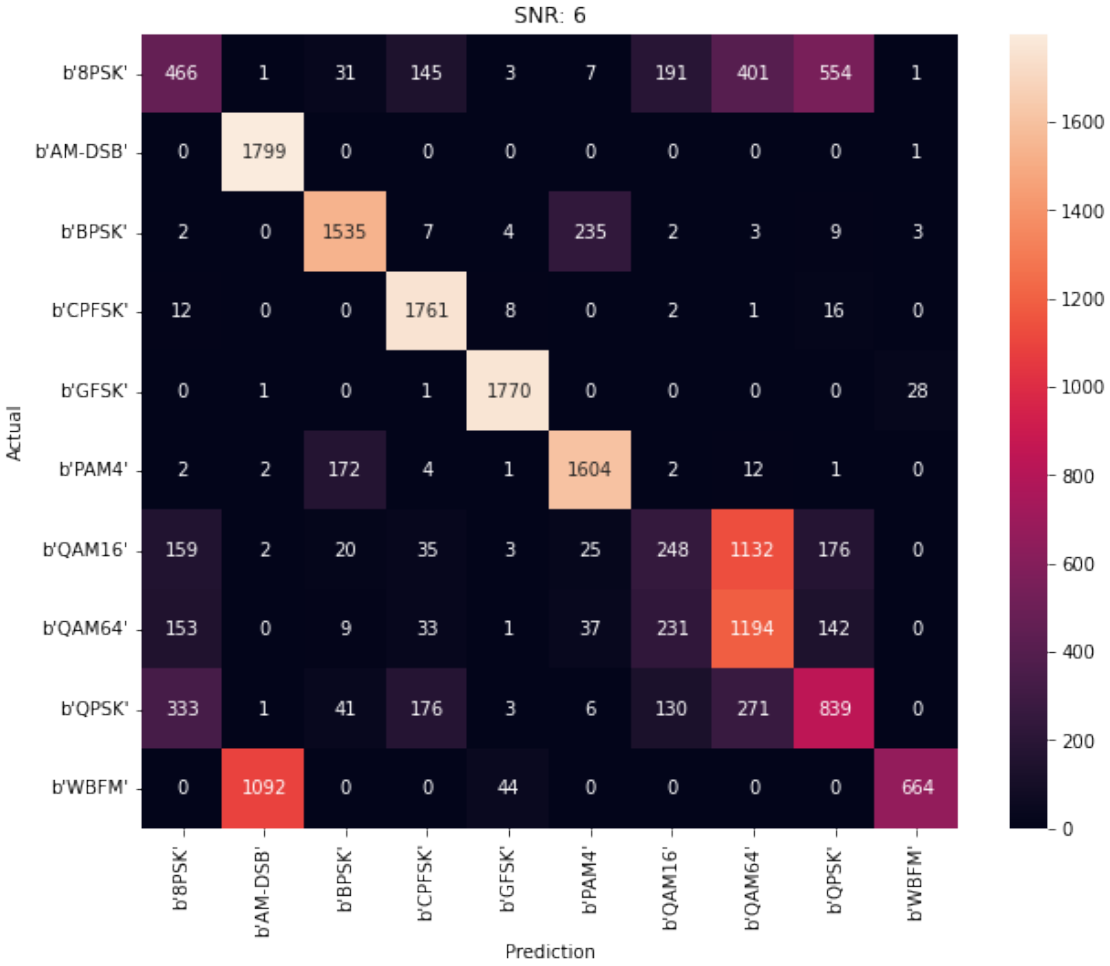

```
Accuracy at SNR = 2 is 0.6416666666666667%
```



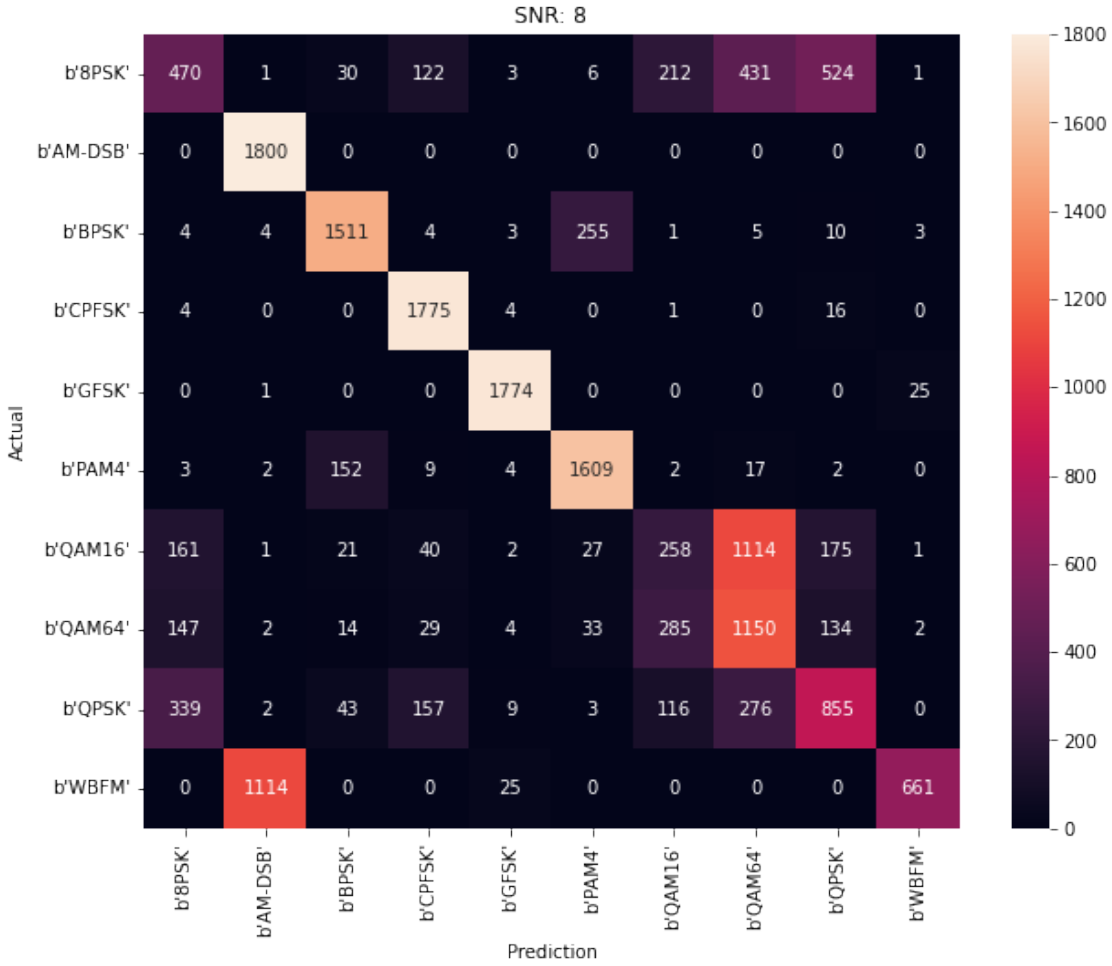

```
Accuracy at SNR = 4 is 0.6548888888888889%
```



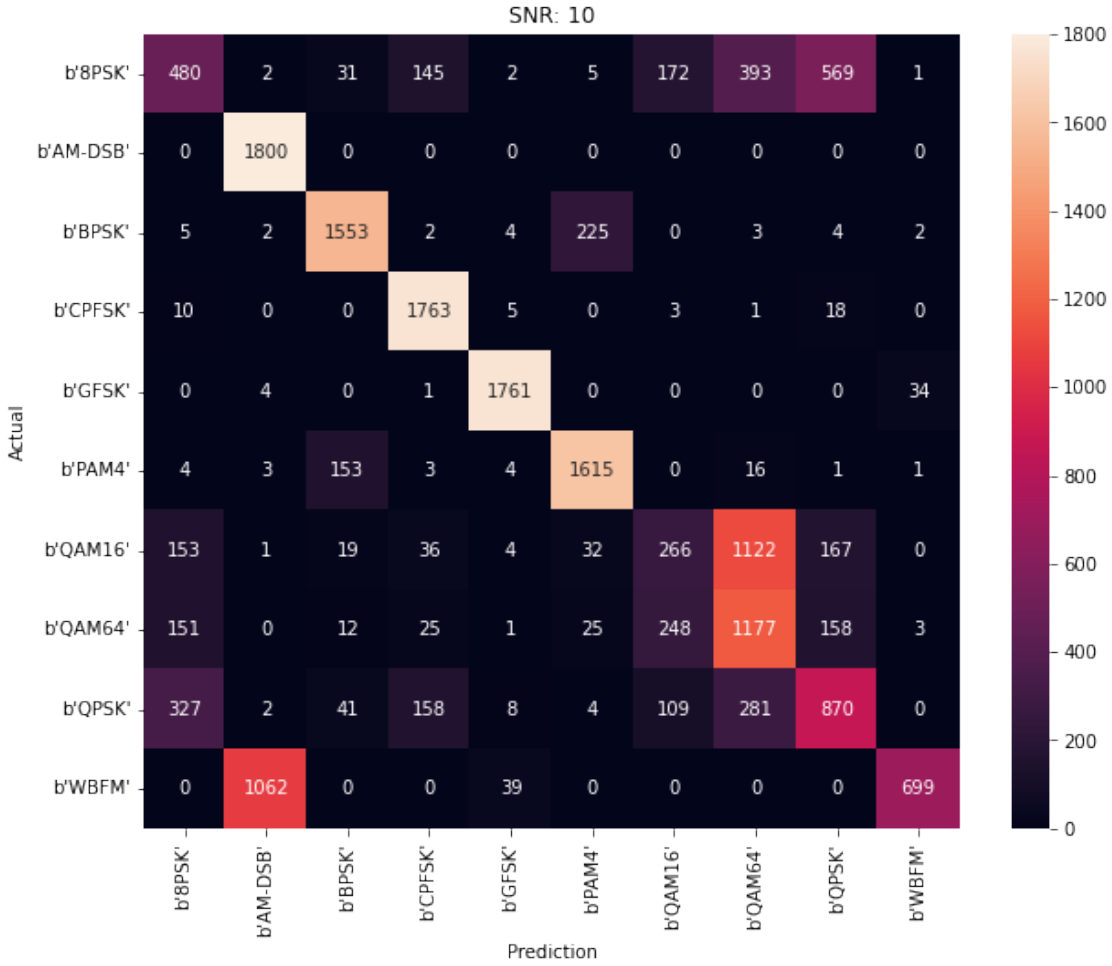

```
Accuracy at SNR = 6 is 0.66%
```



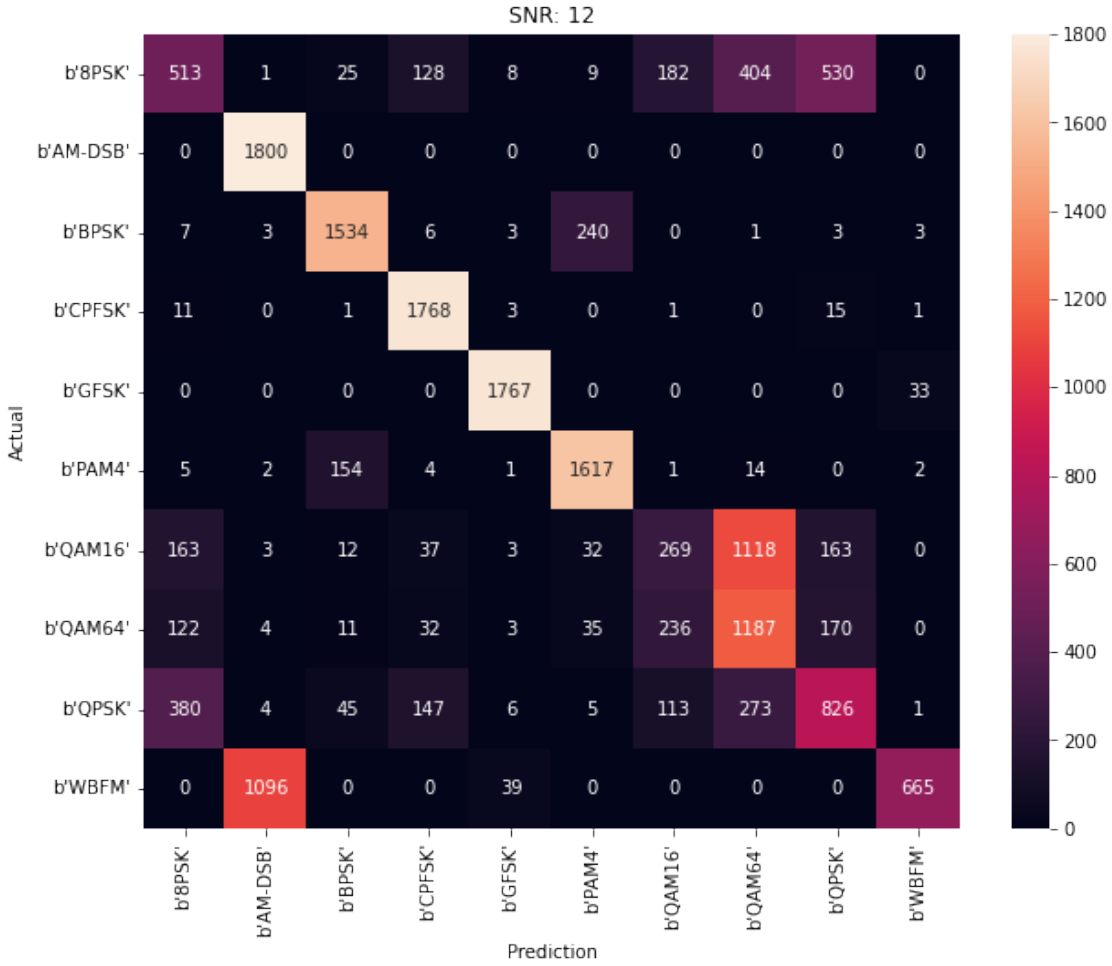

```
Accuracy at SNR = 8 is 0.6590555555555555%
```



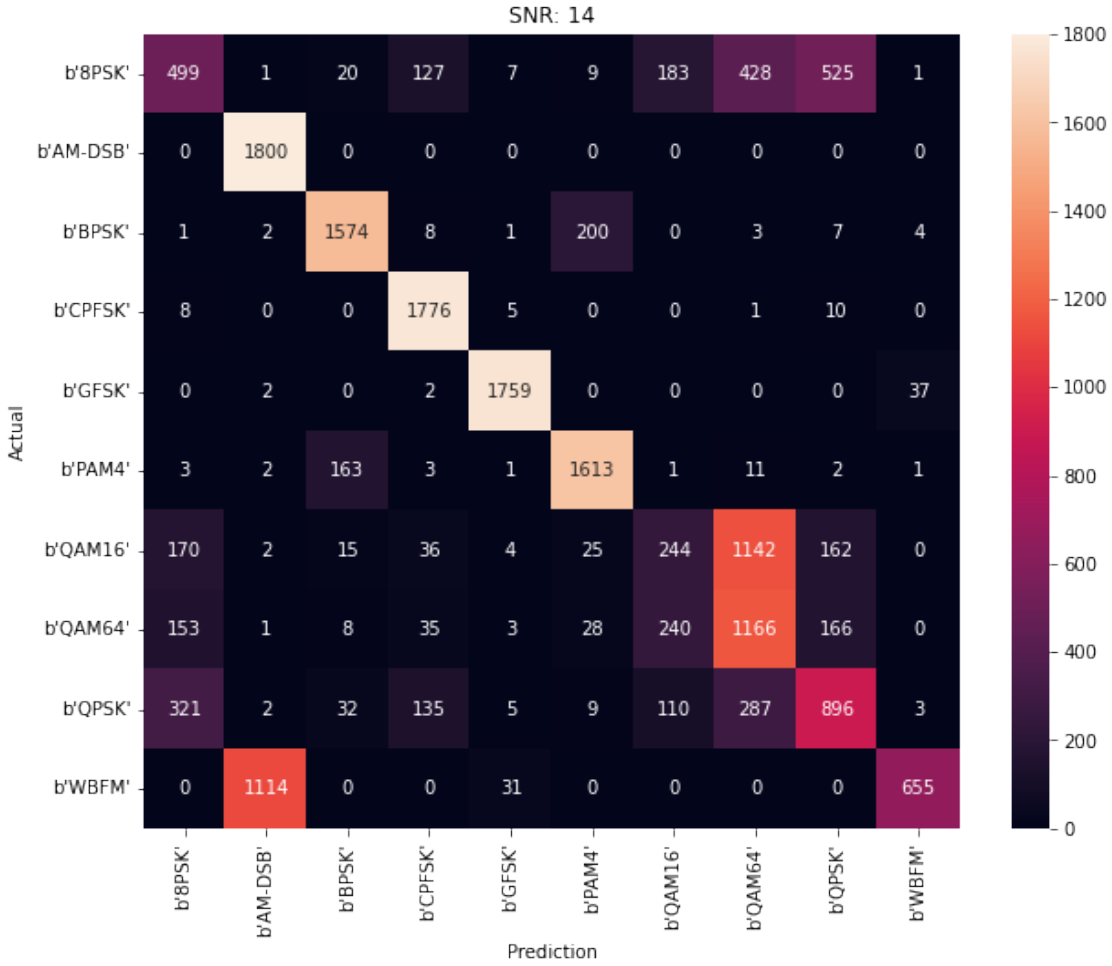
Accuracy at SNR = 10 is 0.6657777777777778%



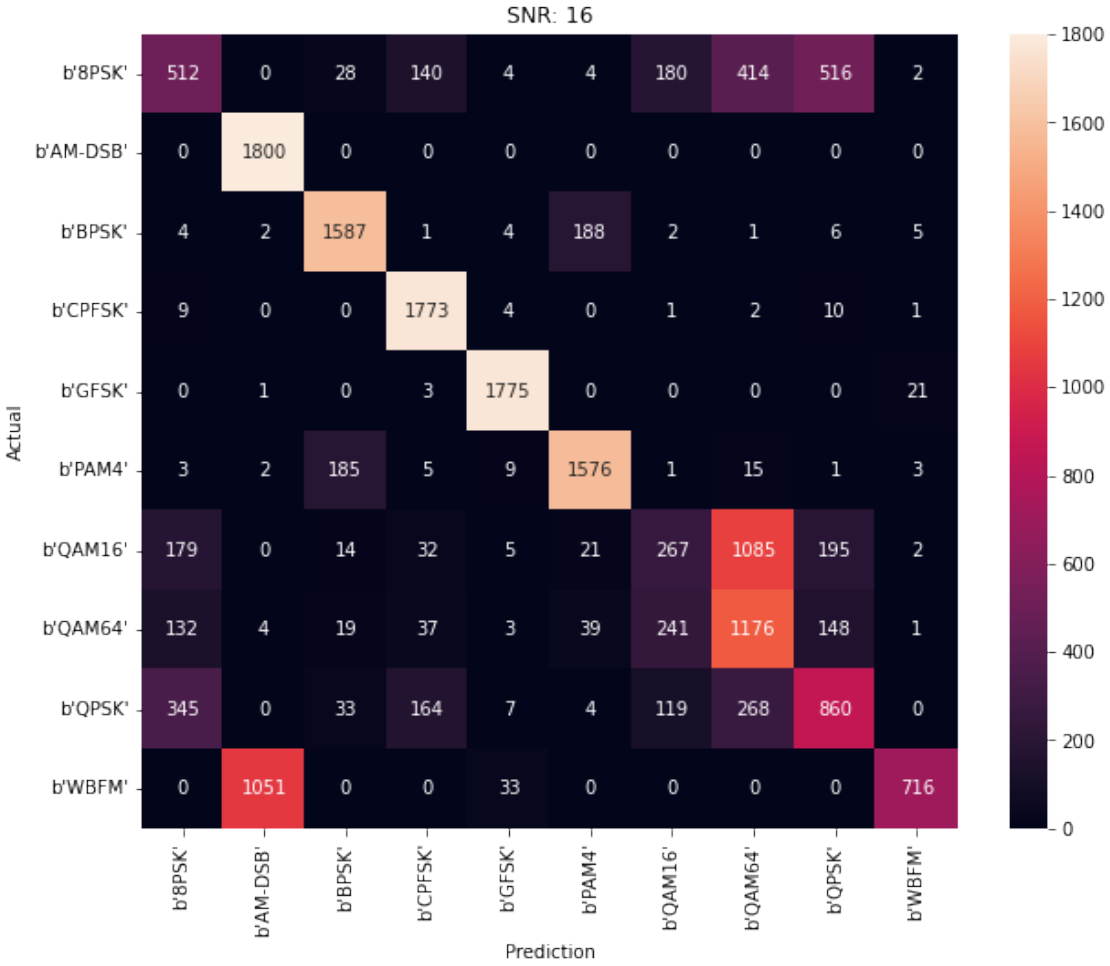

```
Accuracy at SNR = 12 is 0.6636666666666666%
```



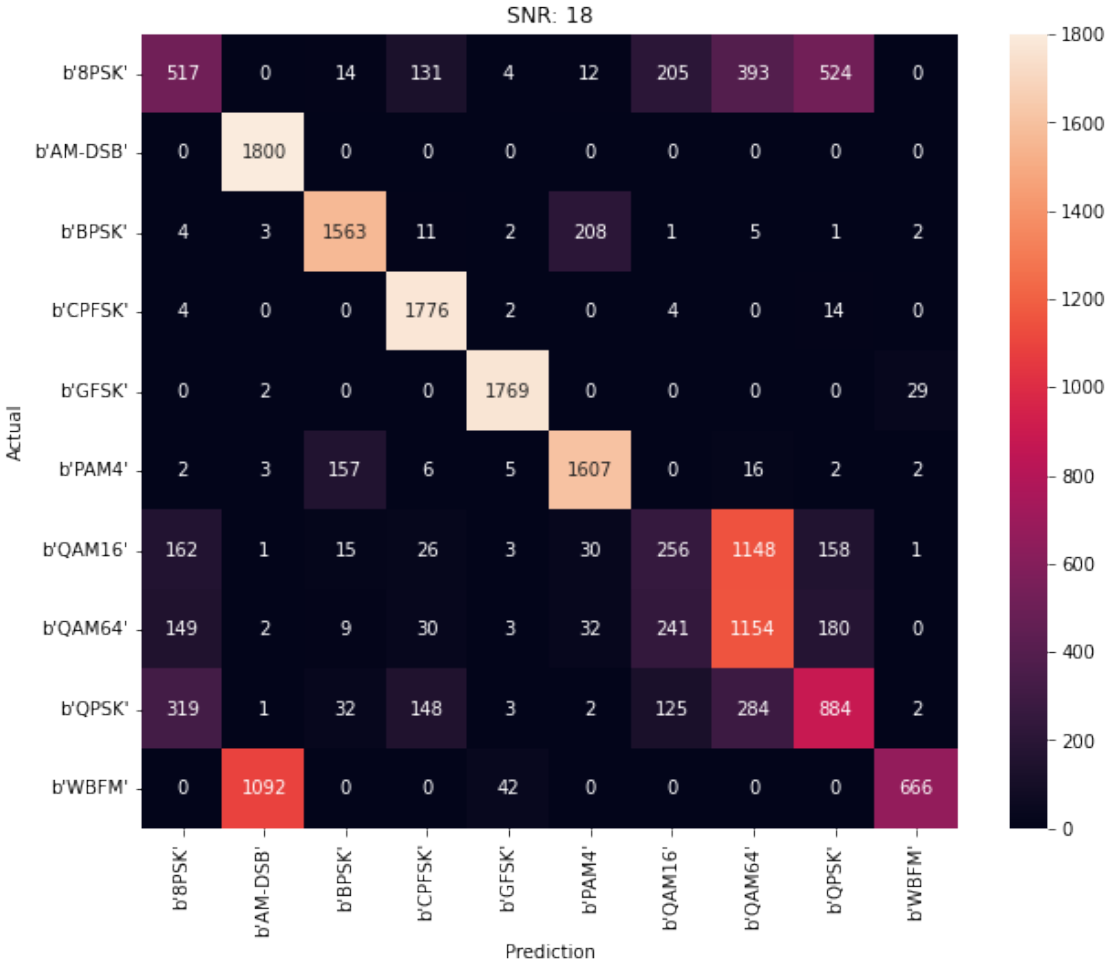
Accuracy at SNR = 14 is 0.6656666666666666%

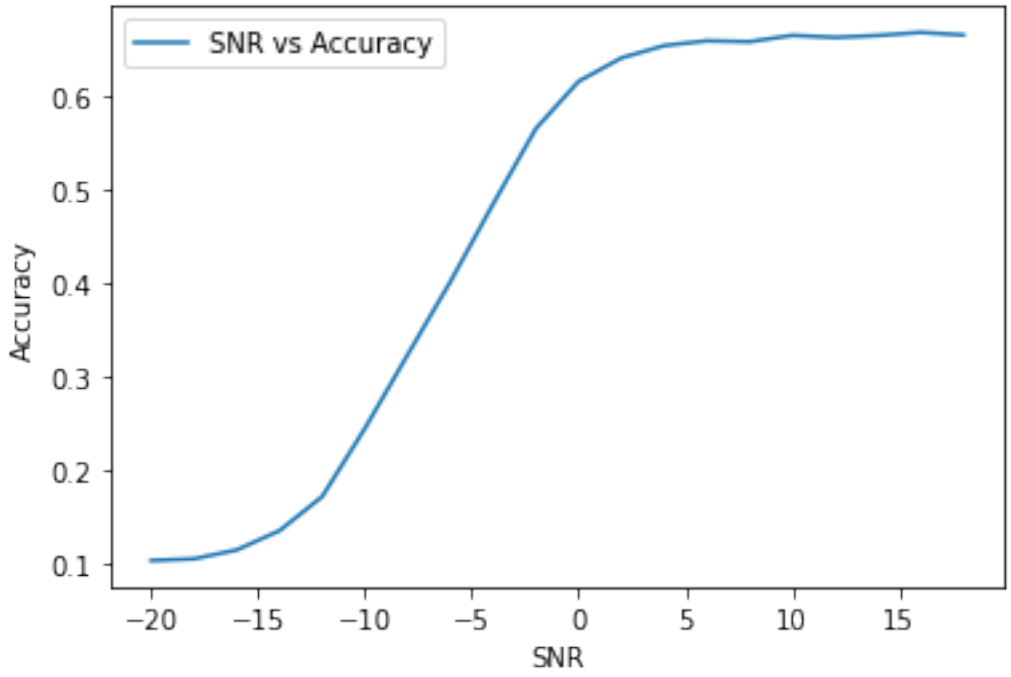



```
Accuracy at SNR = 16 is 0.669%
```




```
Accuracy at SNR = 18 is 0.6662222222222223%
```


SNR: 18
b'8PSK' 517 0 14 131 4 12 205 393 524 0
b'AM-DSB' 0 1800 0 0 0 0 0 0 0 0
b'BPSK' 4 3 1563 11 2 208 1 5 1 2
b'CPFSK' 4 0 0 1776 2 0 4 0 14 0
b'GFSK' 0 2 0 0 1769 0 0 0 0 29
b'PAM4' 2 3 157 6 5 1607 0 16 2 2
b'QAM16' 162 1 15 26 3 30 256 1148 158 1
b'QAM64' 149 2 9 30 3 32 241 1154 180 0
b'QPSK' 319 1 32 148 3 2 125 284 884 2
b'WBFM' 0 1092 0 0 42 0 0 0 0 666
Actual
b'8PSK' b'AM-DSB' b'BPSK' b'CPFSK' b'GFSK' b'PAM4' b'QAM16' b'QAM64' b'QPSK' b'WBFM'
Prediction
1800 1600 1400 1200 1000 800 600 400 200 0



8.4 LSTM Model

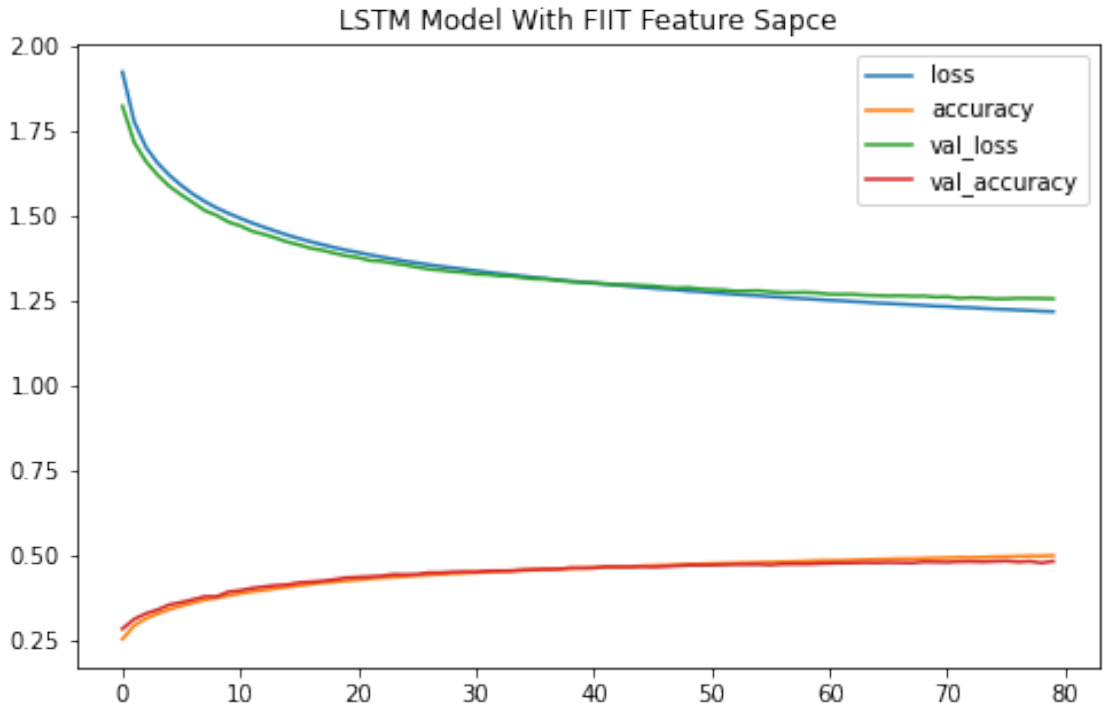
[41]:
```
learning_rate = 0.001
batch_size = 512
epochs = 200
```

[42]:
```
lstm_model = Sequential()
lstm_model.add(LSTM(256))
lstm_model.add(Dropout(0.2))
lstm_model.add(Dense(10, activation='softmax'))
lstm_model.compile(loss=tf.keras.losses.CategoricalCrossentropy(),␣
 ↪metrics='accuracy', optimizer=tf.keras.optimizers.
 ↪Adam(learning_rate=learning_rate))
```

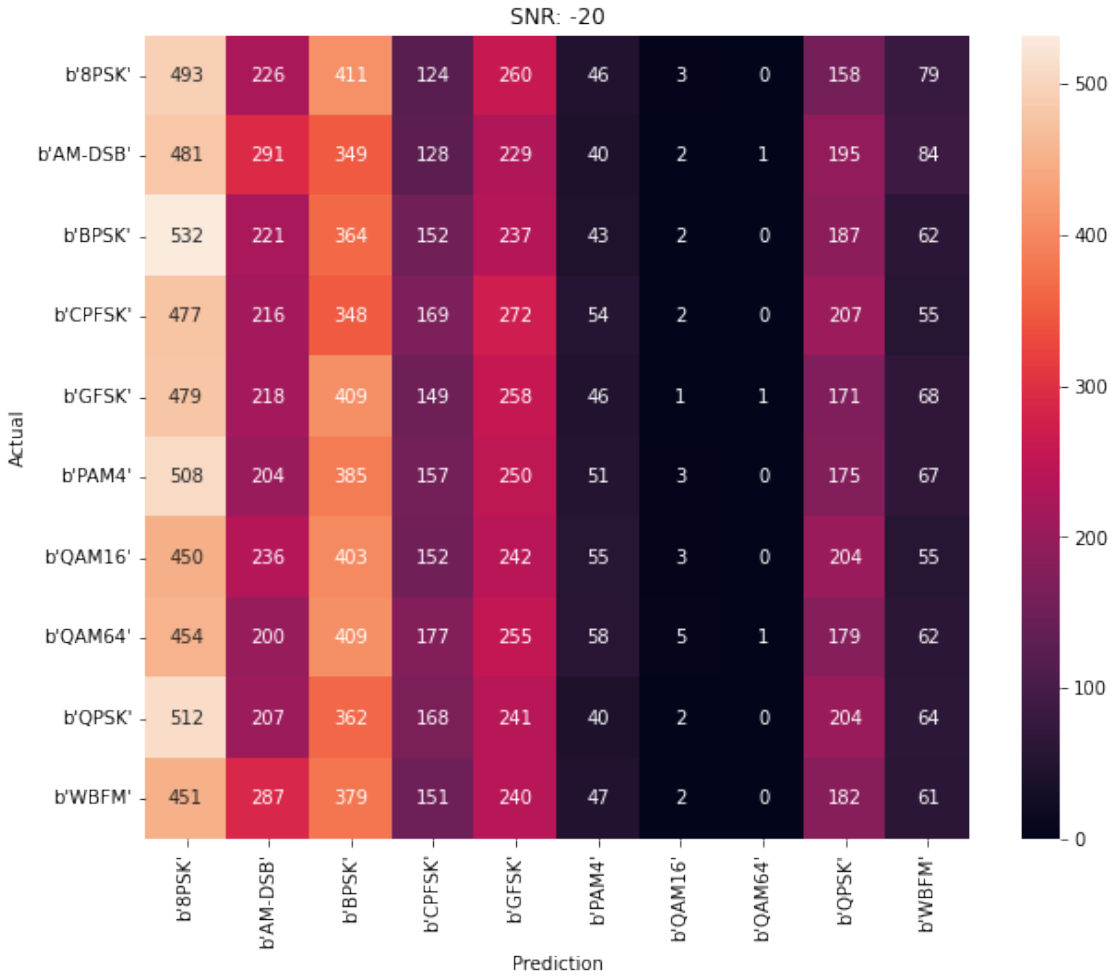
[43]:
```
es = tf.keras.callbacks.EarlyStopping(monitor="val_loss", patience=5,␣
 ↪restore_best_weights=True,)
checkpointer = ModelCheckpoint(filepath='saved_models/lstm_fiit_classification.
 ↪hdf5', verbose=1, save_best_only=True)

with tf.device('/device:GPU:0'):
  history = lstm_model.fit(fiit_training_data, training_onehot,␣
 ↪batch_size=batch_size, epochs=epochs, validation_data=(fiit_validation_data,␣
 ↪validation_onehot), callbacks=[es, checkpointer], verbose=1)
```

```
Epoch 1/200
1550/1559 [============================>.] - ETA: 0s - loss: 1.9231 - accuracy:
0.2506
Epoch 1: val_loss improved from inf to 1.82238, saving model to
saved_models/lstm_fiit_classification.hdf5
1559/1559 [==============================] - 11s 5ms/step - loss: 1.9226 -
accuracy: 0.2508 - val_loss: 1.8224 - val_accuracy: 0.2812

Epoch 80: val_loss did not improve from 1.25417
1559/1559 [==============================] - 8s 5ms/step - loss: 1.2165 -
accuracy: 0.4971 - val_loss: 1.2544 - val_accuracy: 0.4803
```

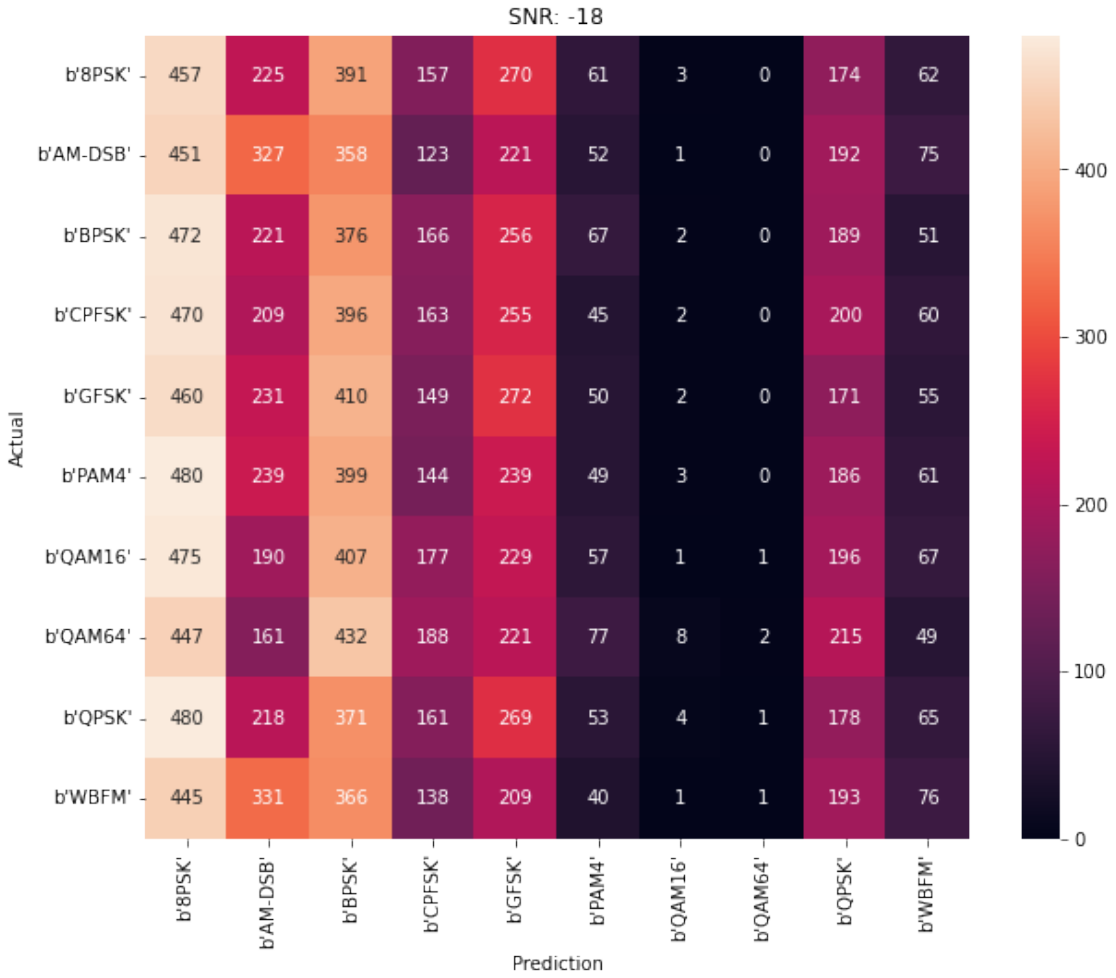
[44]:
```
plot_model_history(history, 'LSTM Model With FIIT Feature Sapce')
model_scoring(lstm_model, history, fiit_testing_data, testing_pair_labels)
```



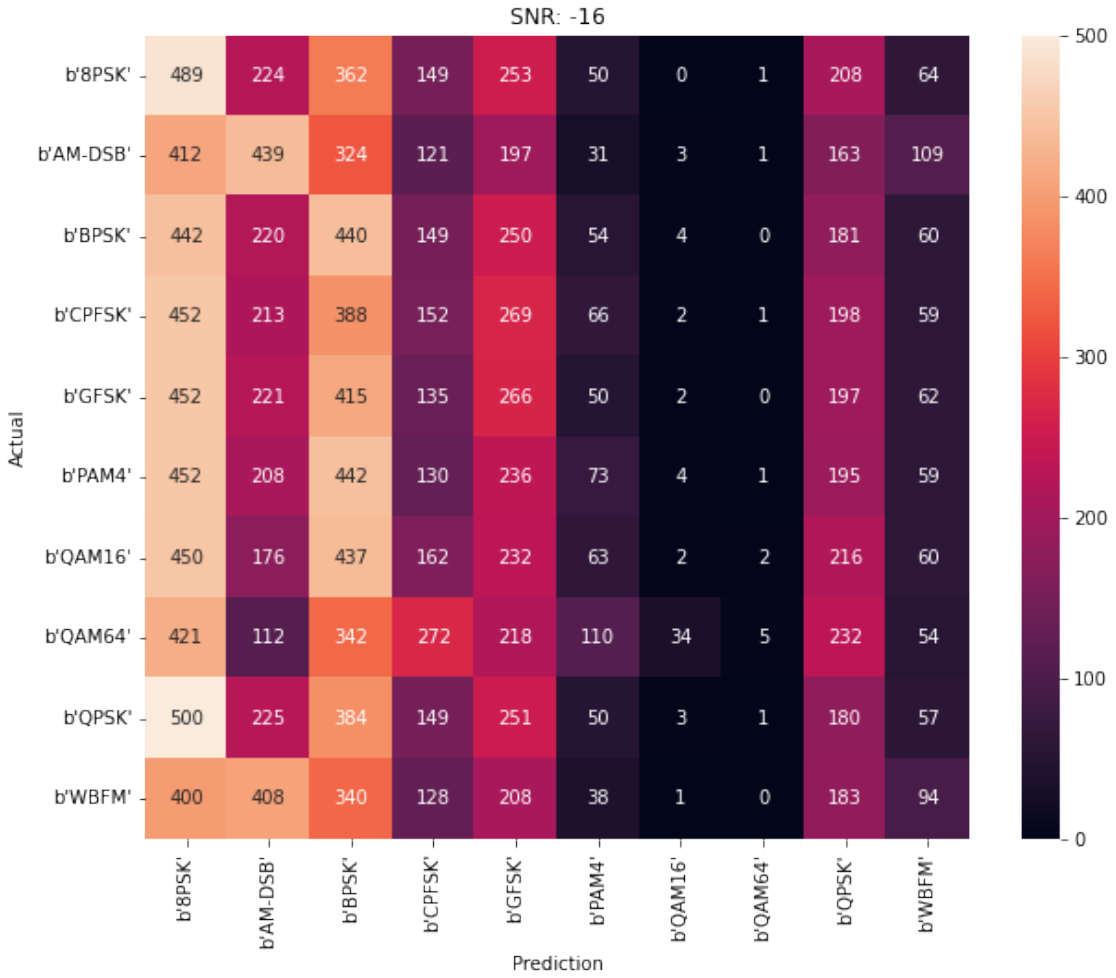

```
Accuracy at SNR = -20 is 0.10527777777777778%
```



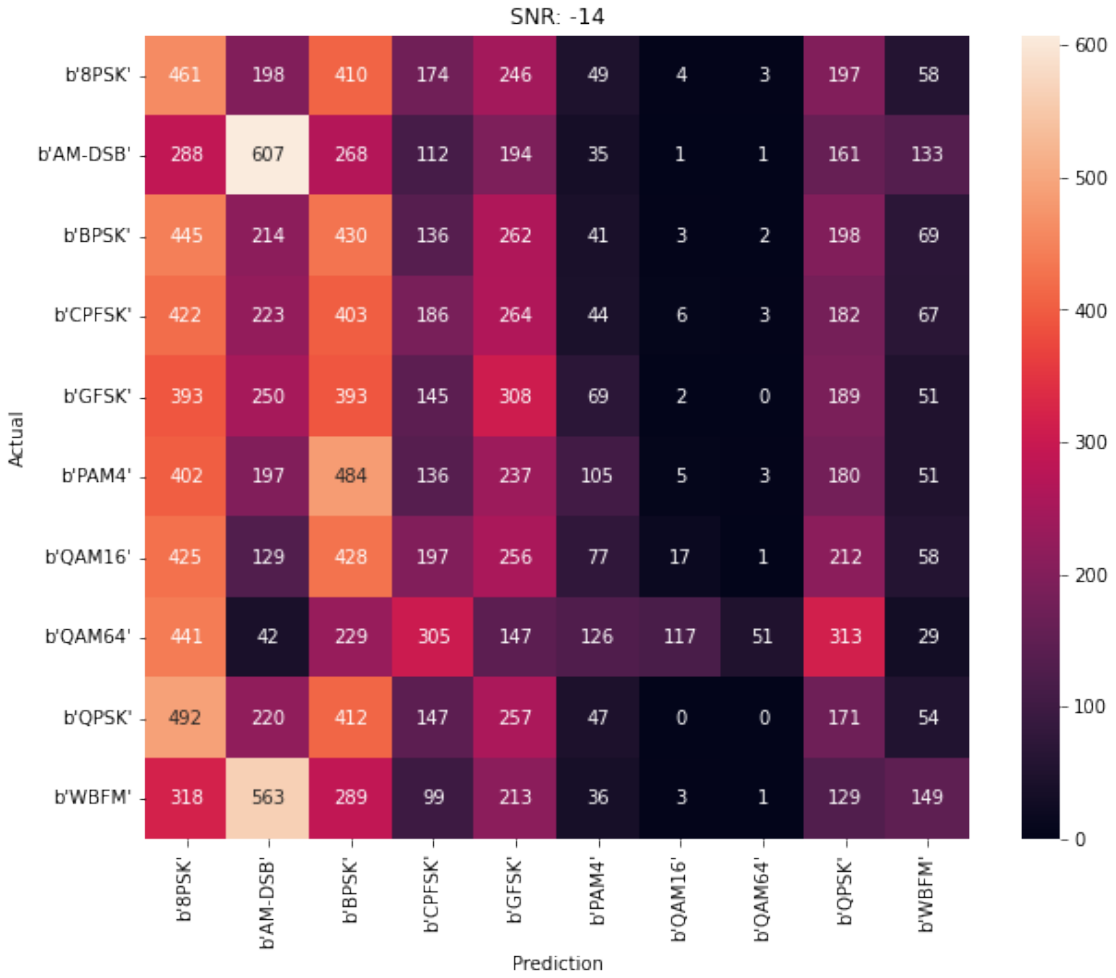
Accuracy at SNR = -18 is 0.10561111111111111%



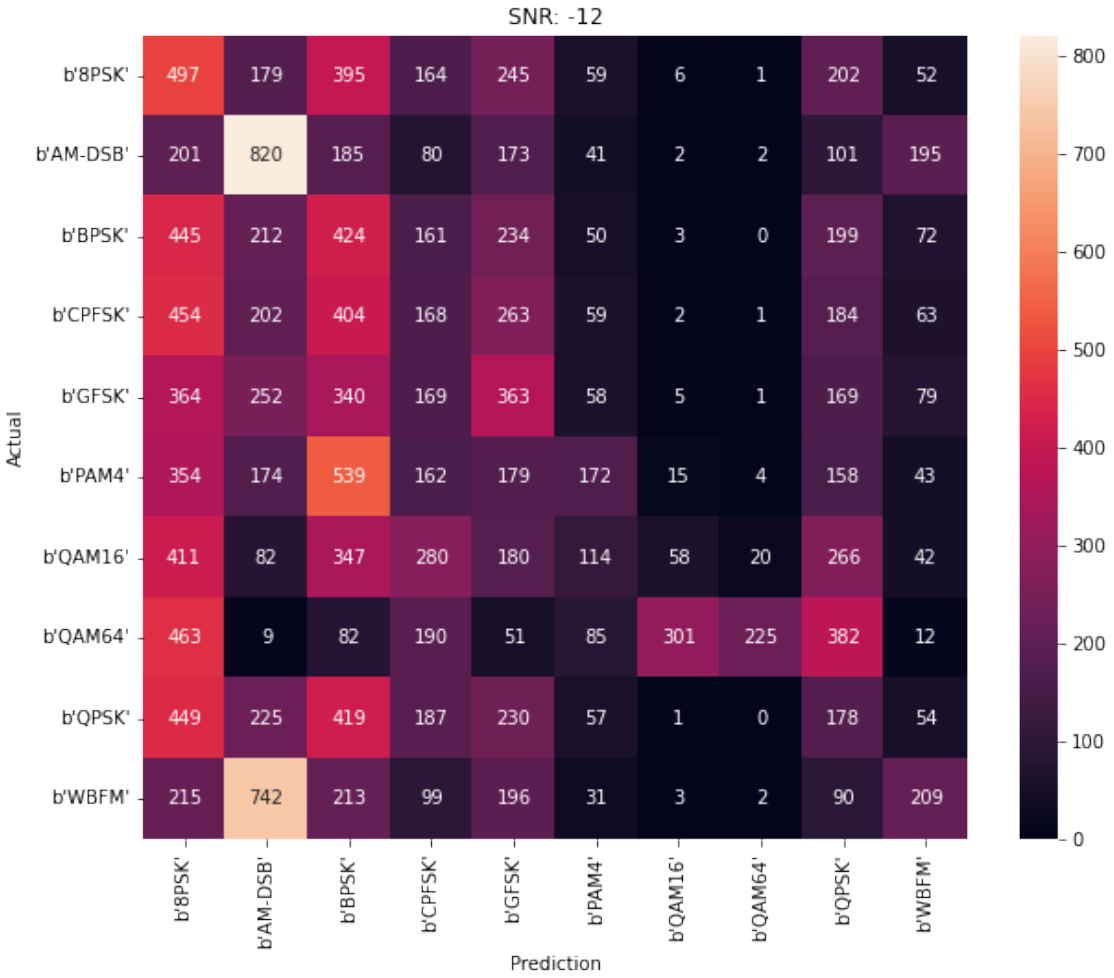

```
Accuracy at SNR = -16 is 0.11888888888888889%
```



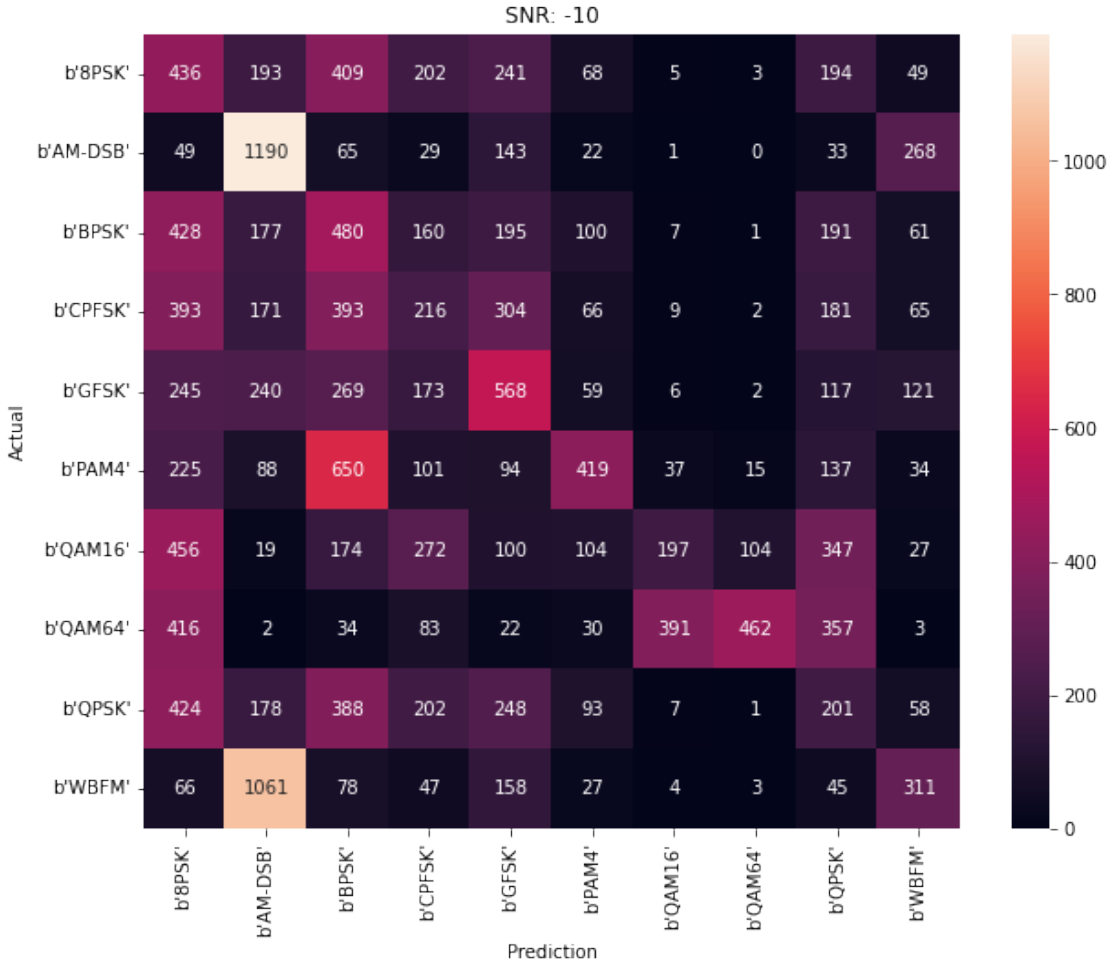

```
Accuracy at SNR = -14 is 0.13805555555555554%
```



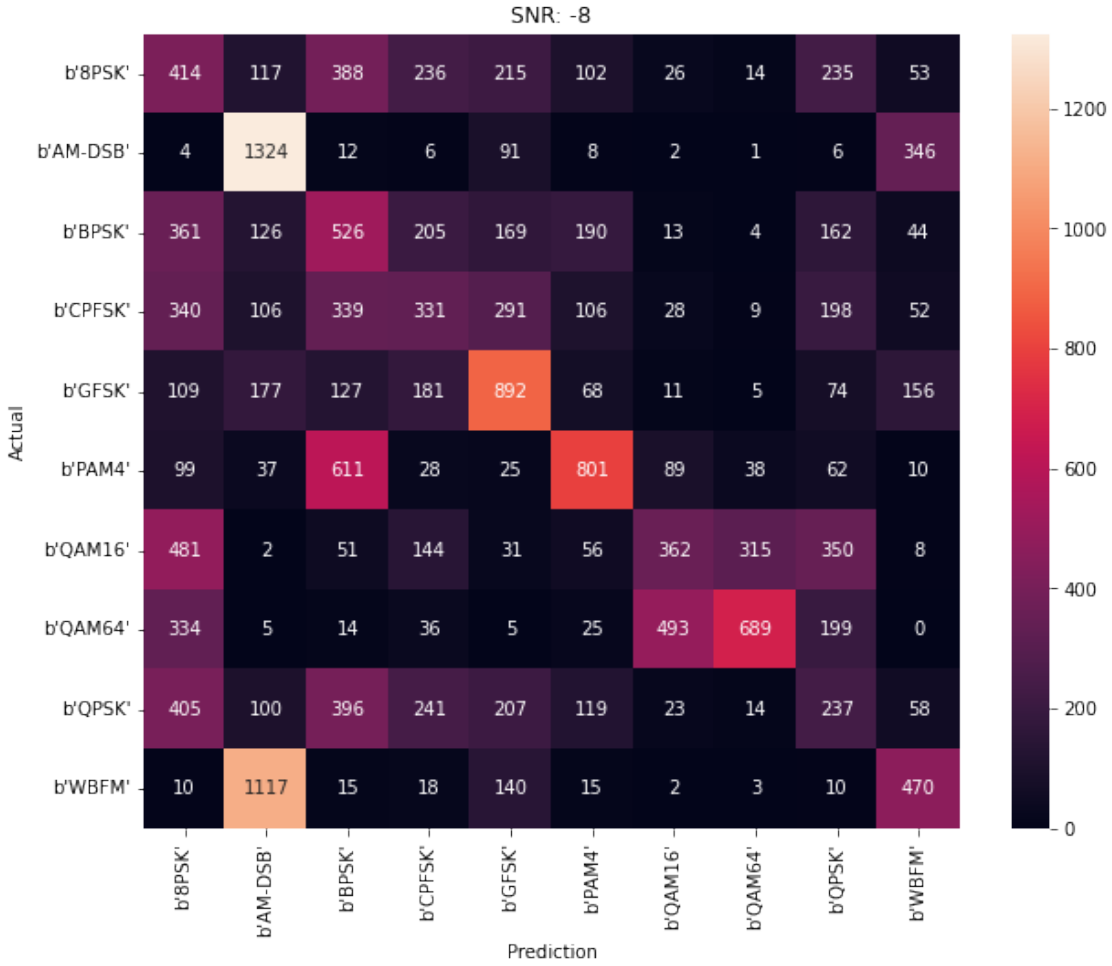

```
Accuracy at SNR = -12 is 0.173%
```



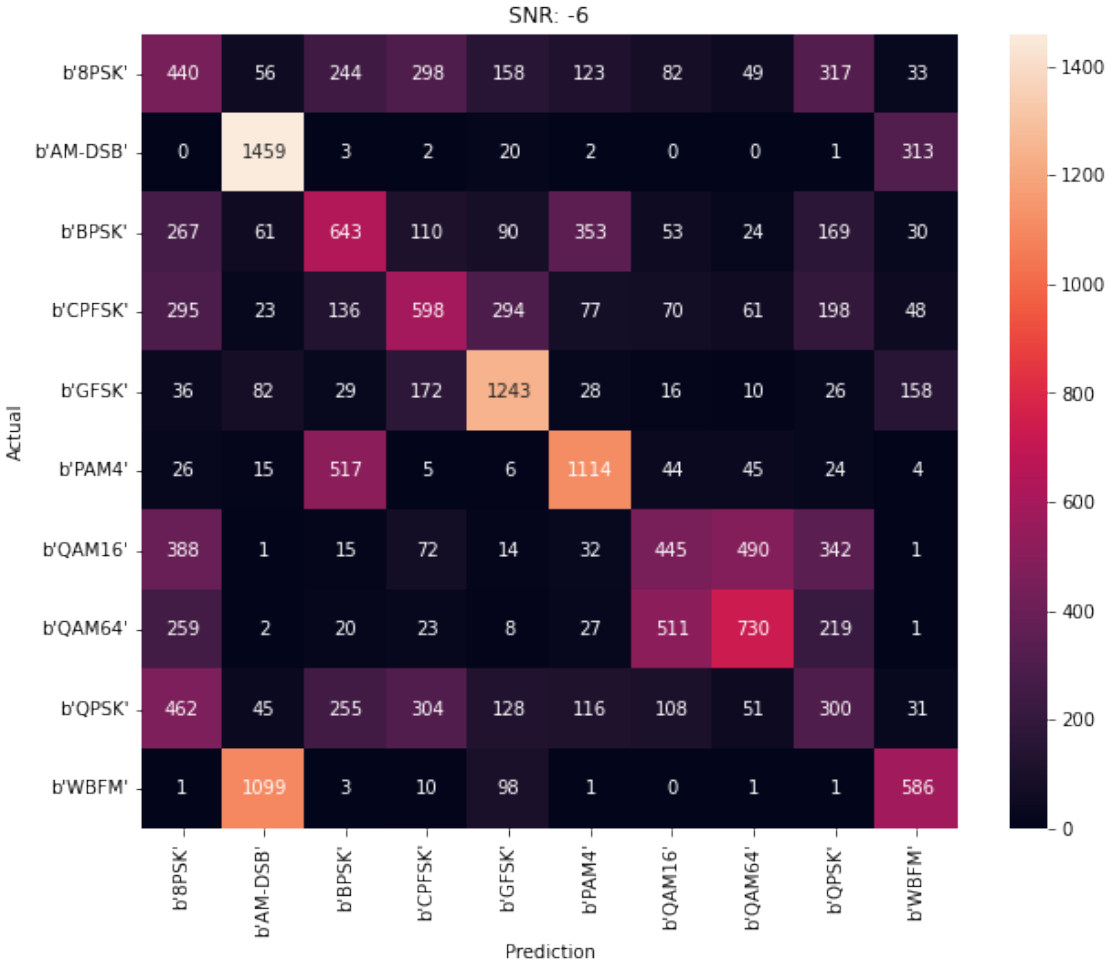

```
Accuracy at SNR = -10 is 0.24888888888888888%
```



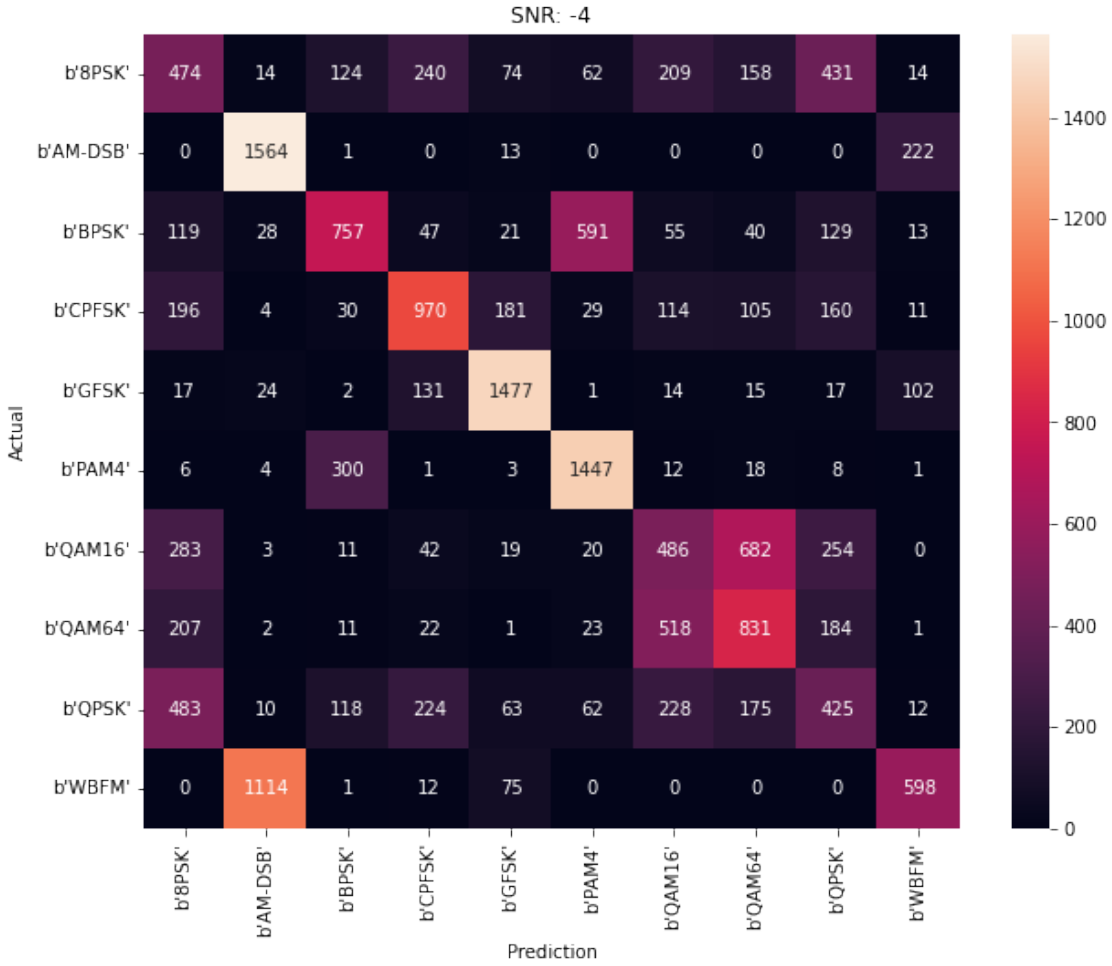

```
Accuracy at SNR = -8 is 0.3358888888888889%
```



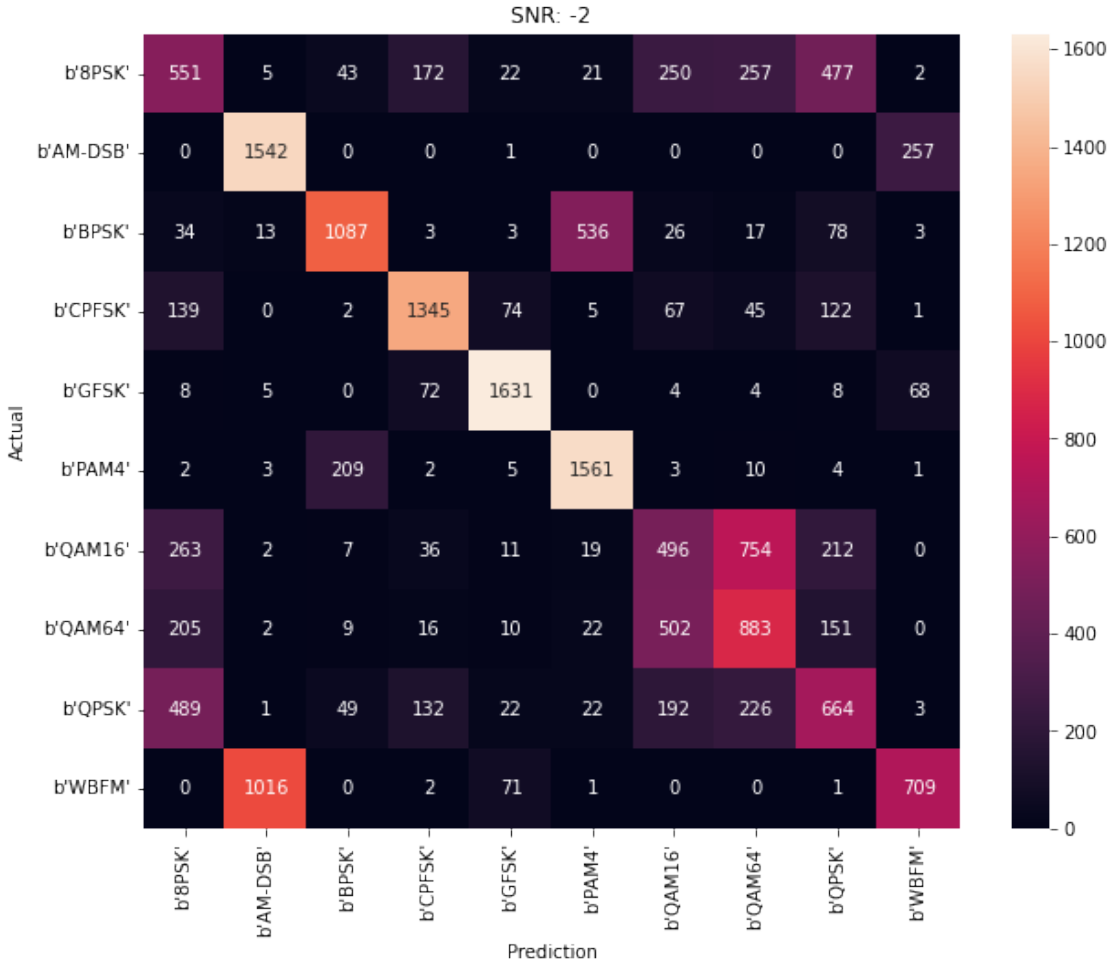

```
Accuracy at SNR = -6 is 0.41988888888888887%
```



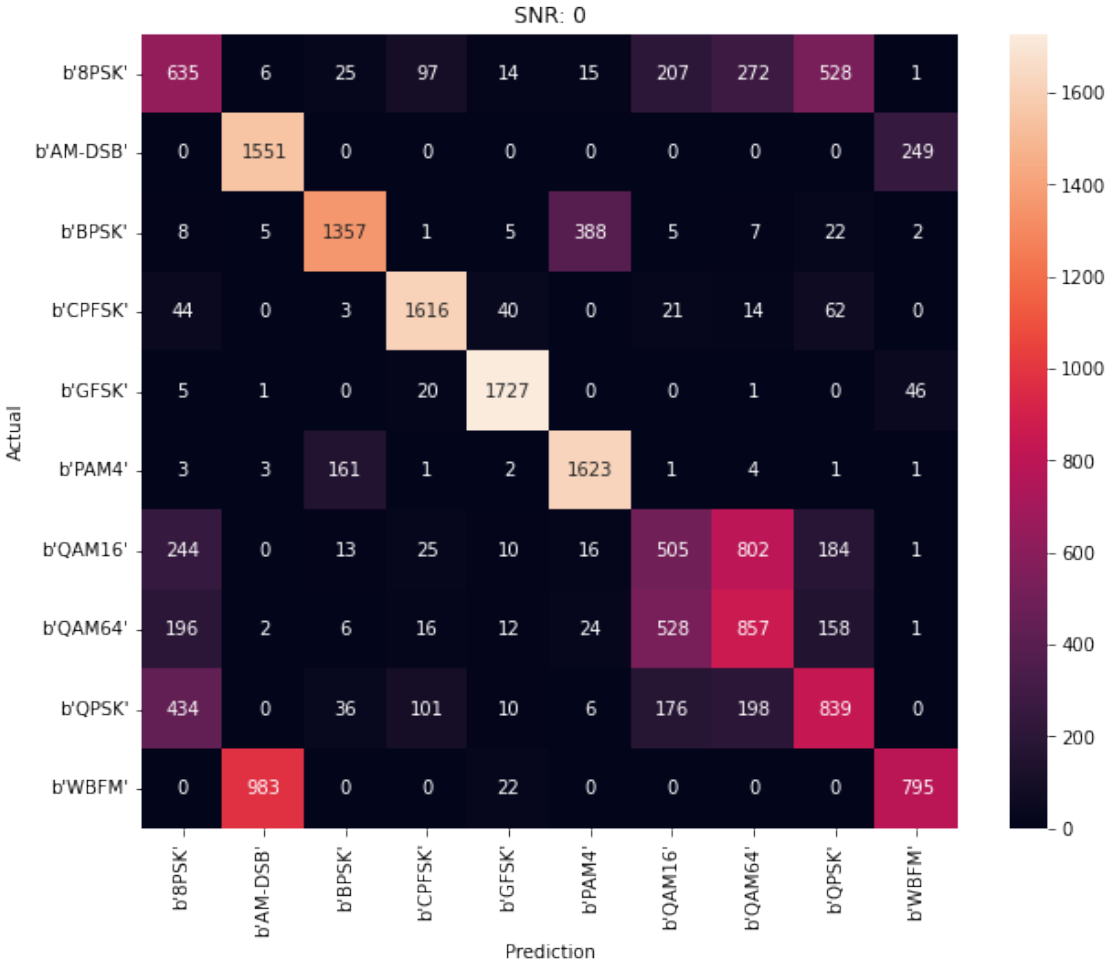

```
Accuracy at SNR = -4 is 0.5016111111111111%
```



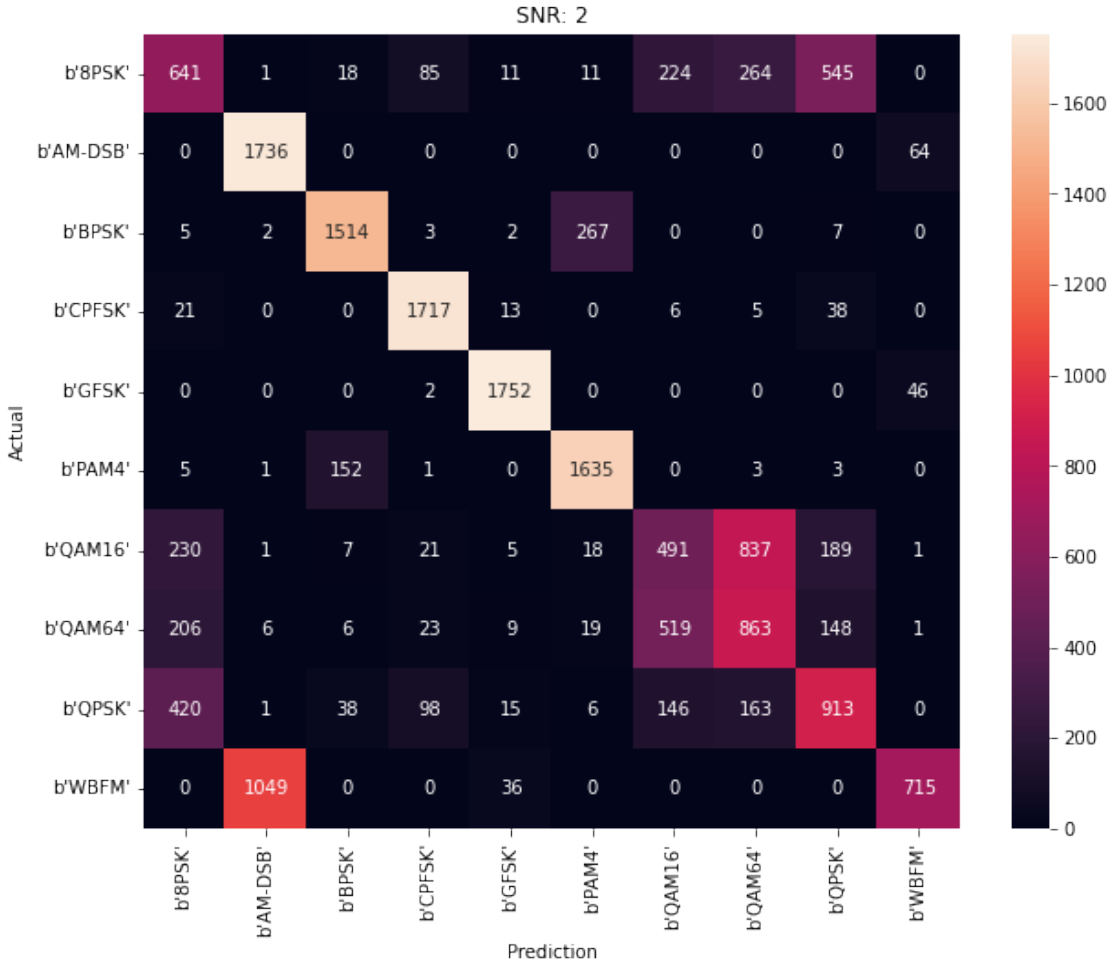

```
Accuracy at SNR = -2 is 0.5816111111111111%
```



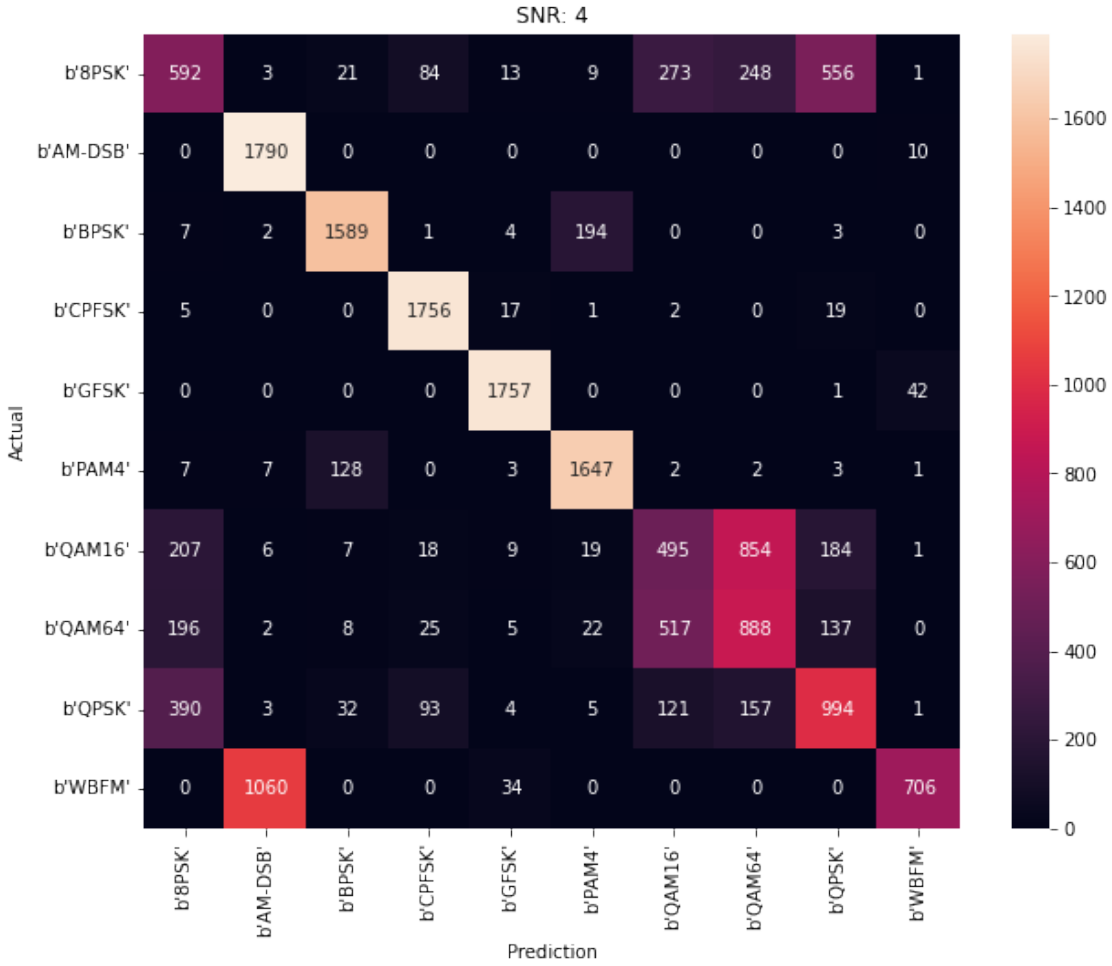

```
Accuracy at SNR = 0 is 0.6391666666666667%
```



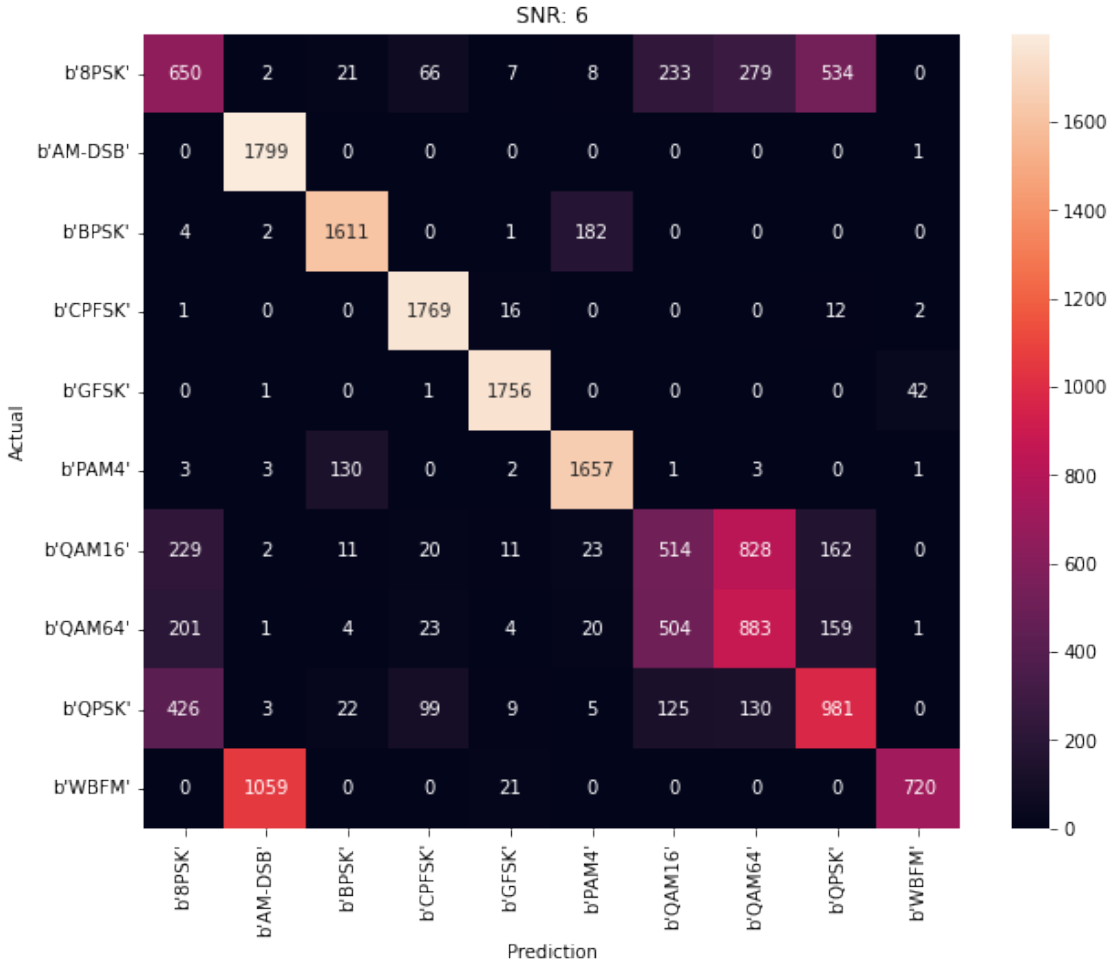

```
Accuracy at SNR = 2 is 0.6653888888888889%
```



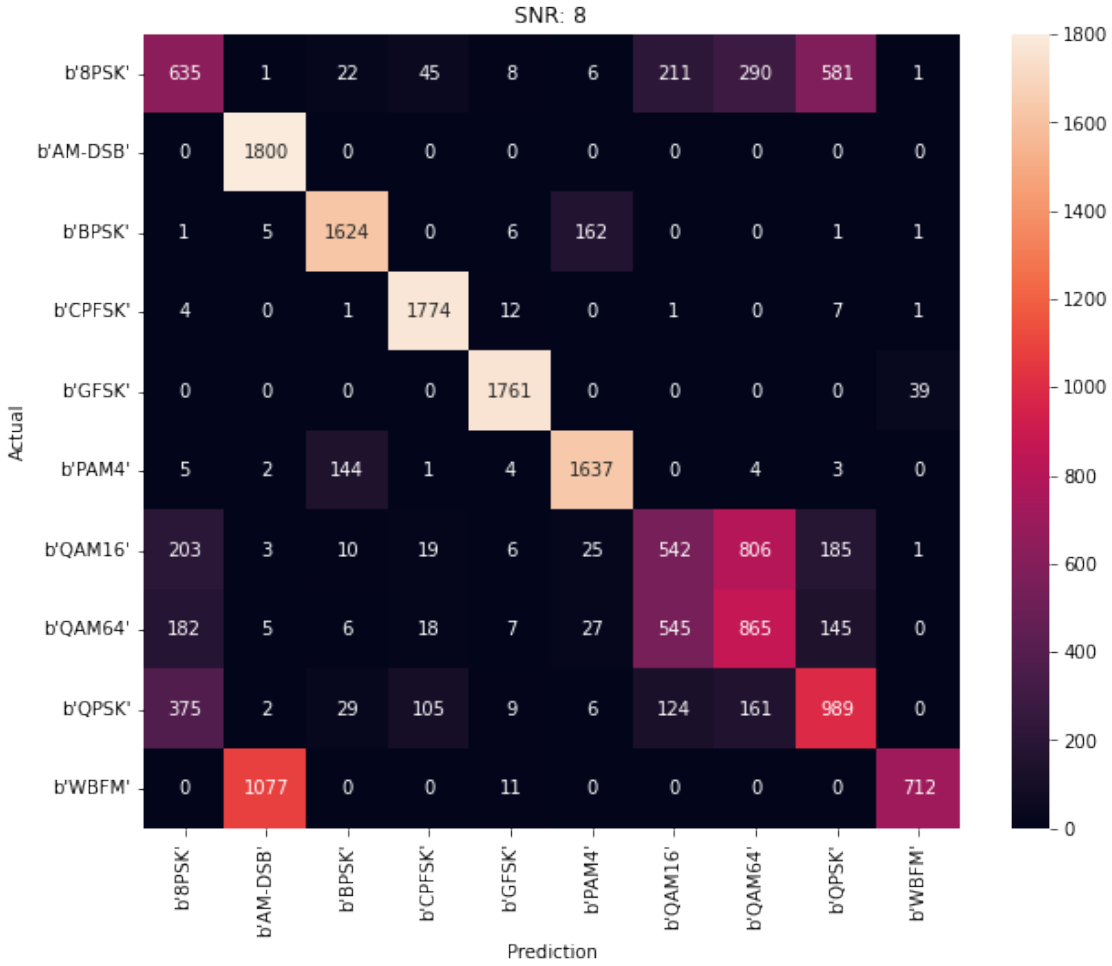

```
Accuracy at SNR = 4 is 0.6785555555555556%
```



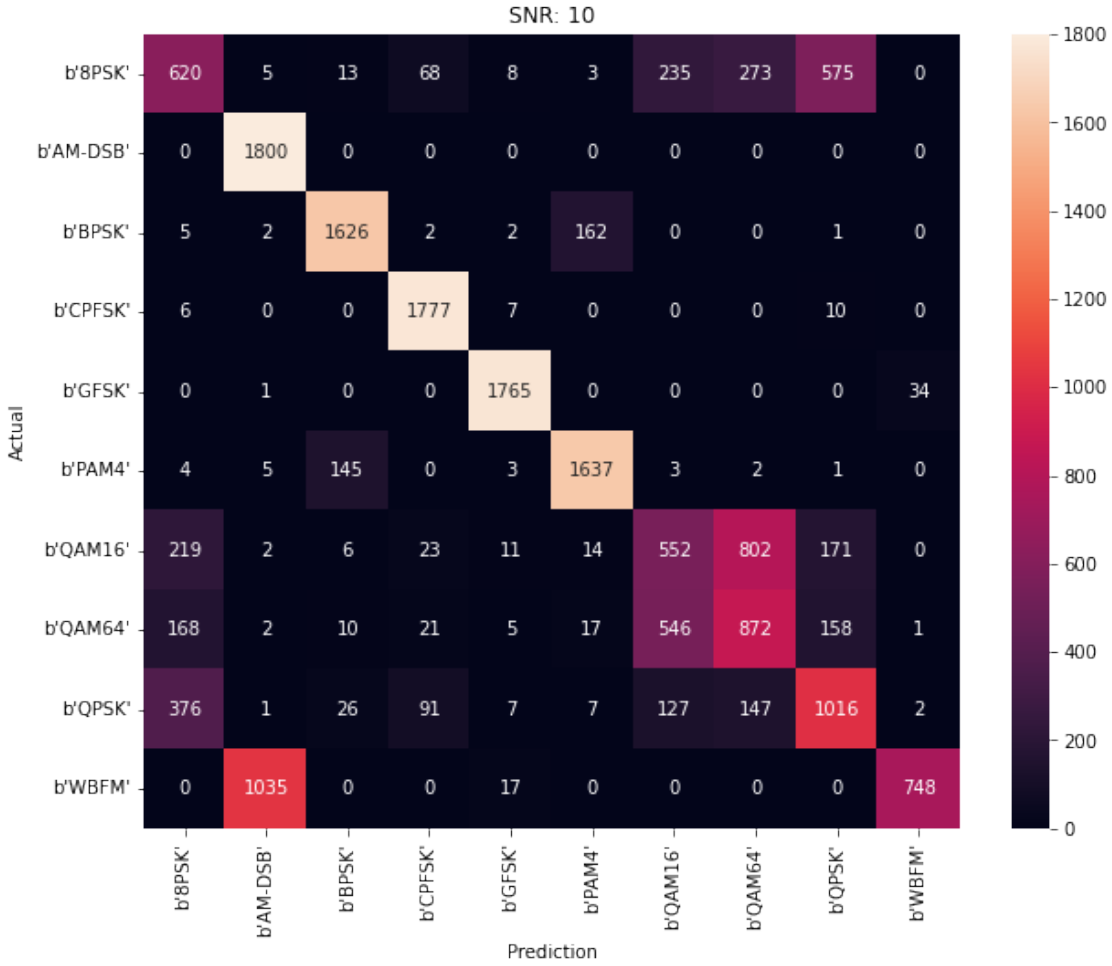

```
Accuracy at SNR = 6 is 0.6855555555555556%
```



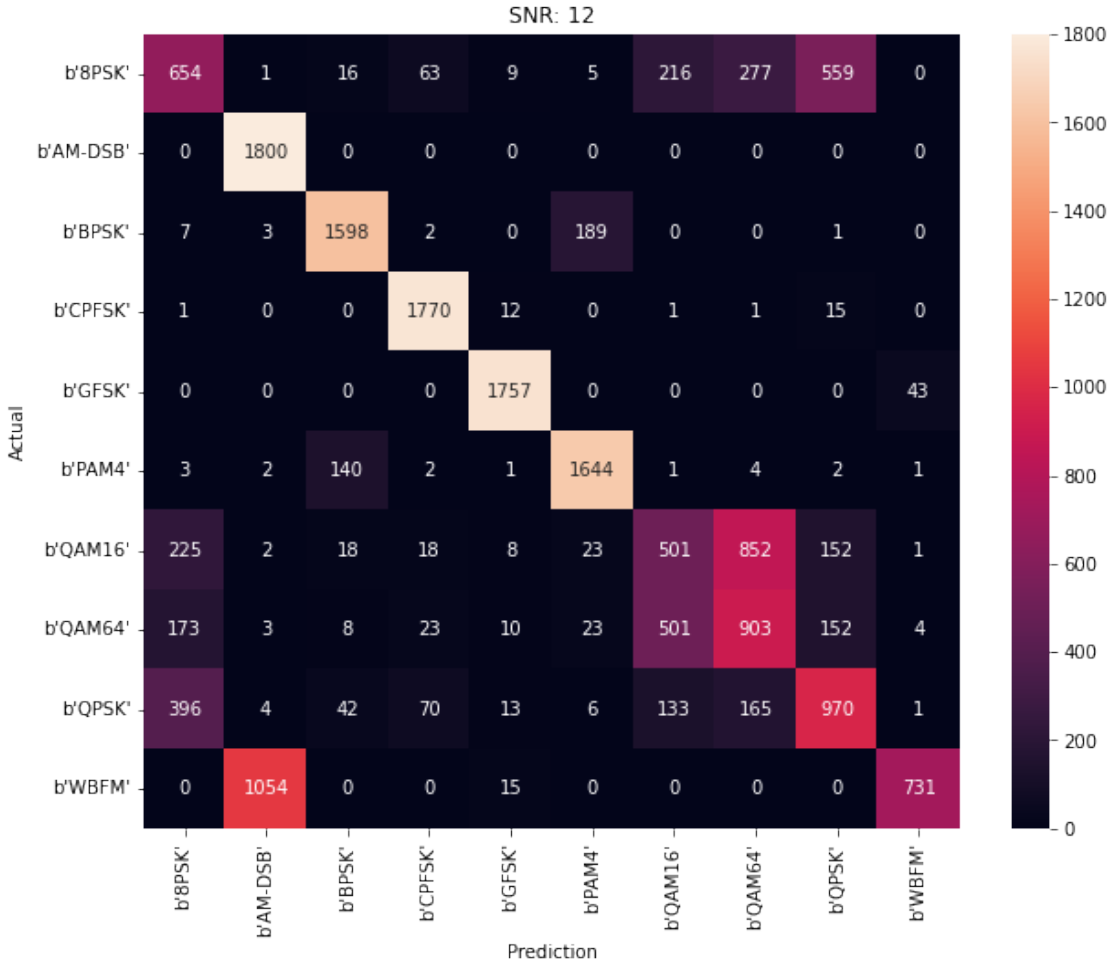

```
Accuracy at SNR = 8 is 0.6855%
```



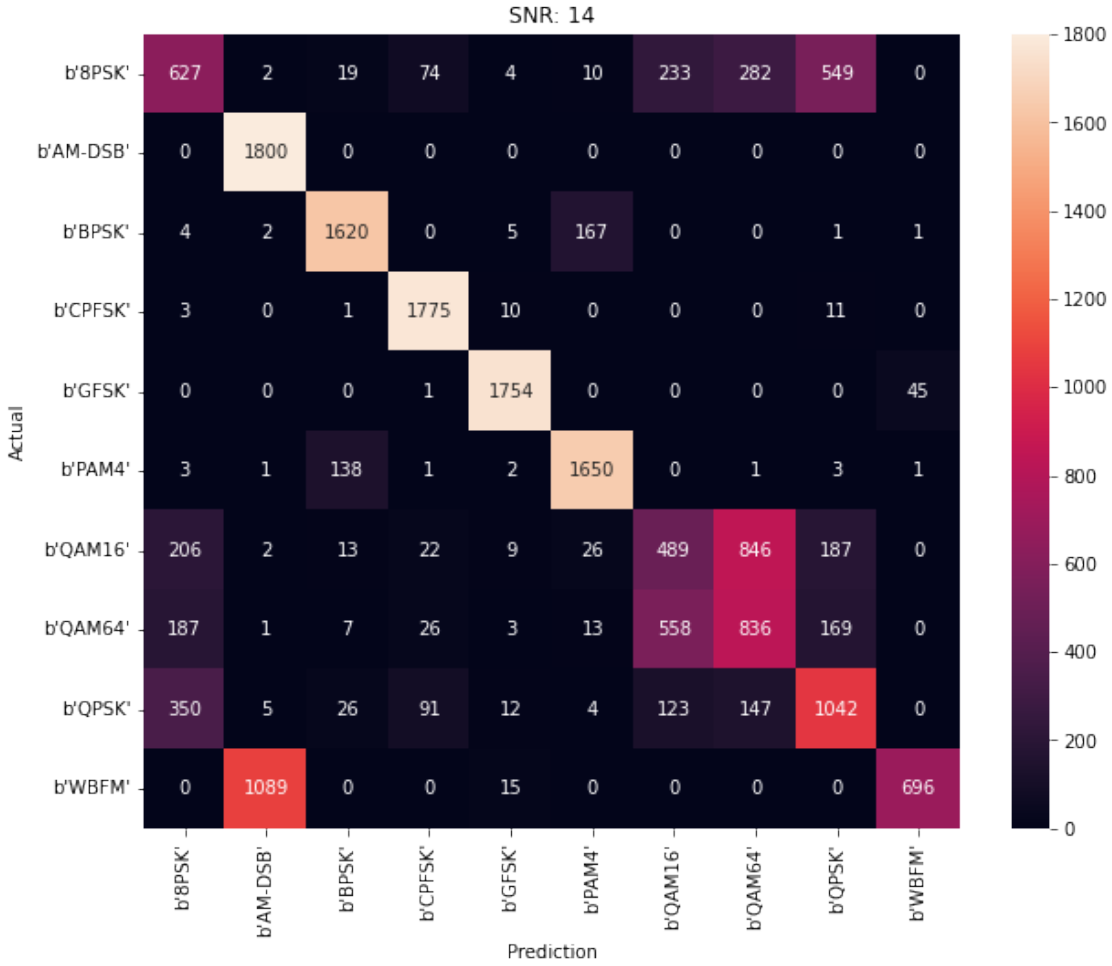

```
Accuracy at SNR = 10 is 0.6896111111111111%
```



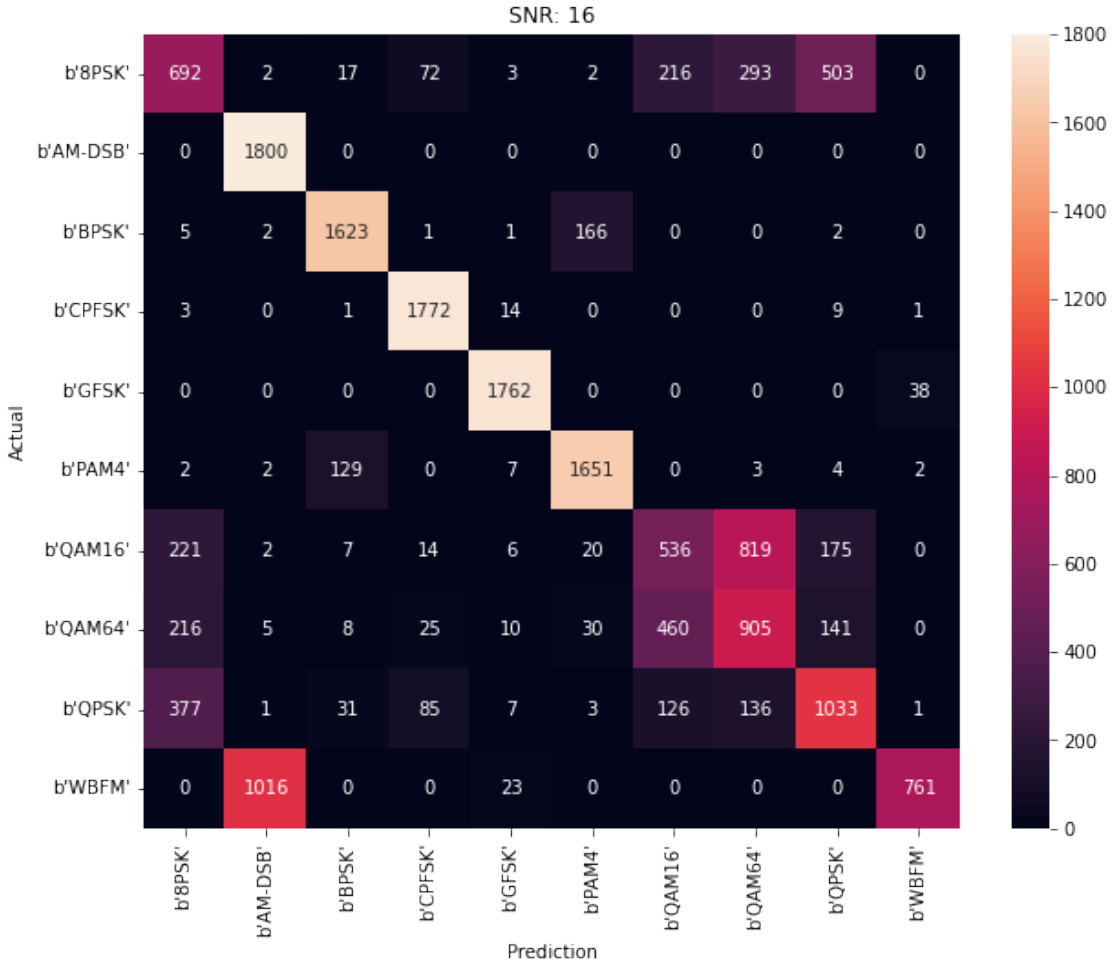
Accuracy at SNR = 12 is 0.6848888888888889%



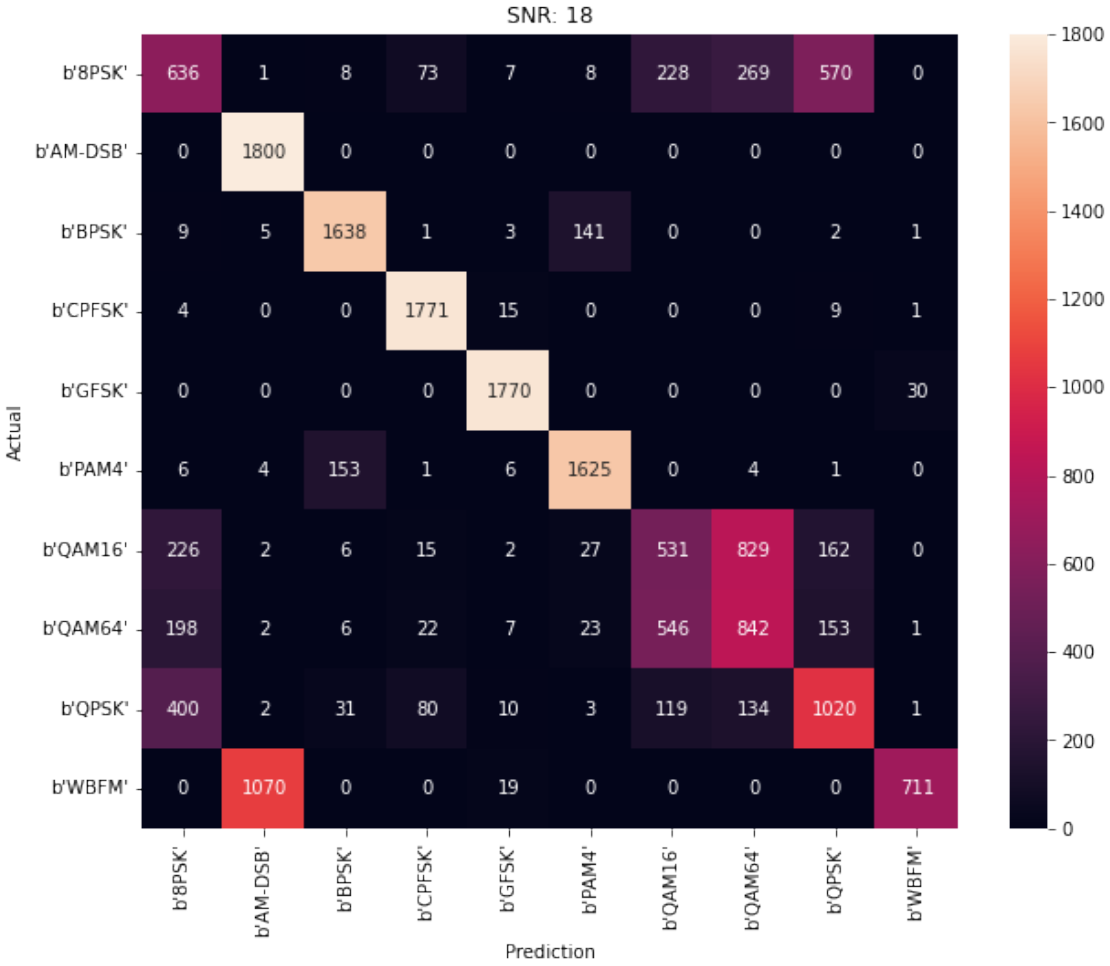

```
Accuracy at SNR = 14 is 0.6827222222222222%
```

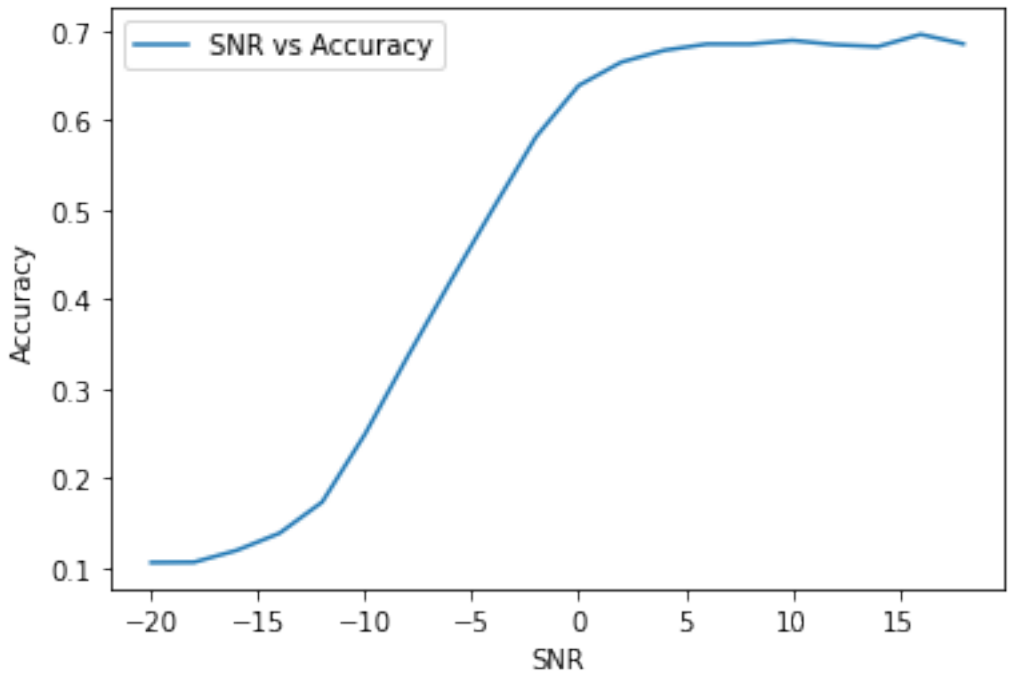



```
Accuracy at SNR = 16 is 0.6963888888888888%
```




```
Accuracy at SNR = 18 is 0.6857777777777778%
```


SNR: 18
b'8PSK' 636 1 8 73 7 8 228 269 570 0
b'AM-DSB' 0 1800 0 0 0 0 0 0 0 0
b'BPSK' 9 5 1638 1 3 141 0 0 2 1
b'CPFSK' 4 0 0 1771 15 0 0 0 9 1
b'GFSK' 0 0 0 0 1770 0 0 0 0 30
b'PAM4' 6 4 153 1 6 1625 0 4 1 0
b'QAM16' 226 2 6 15 2 27 531 829 162 0
b'QAM64' 198 2 6 22 7 23 546 842 153 1
b'QPSK' 400 2 31 80 10 3 119 134 1020 1
b'WBFM' 0 1070 0 0 19 0 0 0 0 711
Actual
b'8PSK' b'AM-DSB' b'BPSK' b'CPFSK' b'GFSK' b'PAM4' b'QAM16' b'QAM64' b'QPSK' b'WBFM'
Prediction
1800 1600 1400 1200 1000 800 600 400 200 0



9 Combined Feature Space

[35]:
```
Combined_training_data = np.concatenate((training_data ,fdit_training_data,␣
 ↪fiit_training_data), axis=2)
Combined_validation_data = np.concatenate((validation_data␣
 ↪,fdit_validation_data, fiit_validation_data), axis=2)
Combined_testing_data = np.concatenate((testing_data ,fdit_testing_data,␣
 ↪fiit_testing_data), axis=2)
```

[36]:
```
print('combined training data shape:', fiit_training_data.shape)
print('combined validation data shape:', fiit_validation_data.shape)
print('combined testing data shape:', fiit_testing_data.shape)
```

```
combined training data shape: (798000, 2, 128)
combined validation data shape: (42000, 2, 128)
combined testing data shape: (360000, 2, 128)
```

[37]:
```
del training_data
del fdit_training_data
del fiit_training_data

del validation_data
del fdit_validation_data
```

```
del fiit_validation_data

del testing_data
del fdit_testing_data
del fiit_testing_data
```

9.1 CNN Model

[38]:
```
Combined_training_data, Combined_validation_data, Combined_testing_data =␣
 ↪reshape_data_for_cnn(Combined_training_data, Combined_validation_data,␣
 ↪Combined_testing_data)
```

[39]:
```
print('training data shape:', Combined_training_data.shape)
print('validation data shape:', Combined_validation_data.shape)
print('testing data shape:', Combined_testing_data.shape)
```

```
training data shape: (798000, 2, 384, 1)
validation data shape: (42000, 2, 384, 1)
testing data shape: (360000, 2, 384, 1)
```

[40]:
```
learning_rate = 0.001
batch_size = 512
epochs = 200
```

[41]:
```
cnn_model = Sequential()
cnn_model.add(Conv2D(256, 3, activation='relu', padding='same'))
cnn_model.add(Dropout(0.5))
cnn_model.add(Conv2D(64, 3, strides=2, activation='relu', padding='same'))
cnn_model.add(Dropout(0.5))
cnn_model.add(Flatten())
cnn_model.add(Dense(128, activation='relu' ))
cnn_model.add(Dense(10,  activation='softmax'))
cnn_model.compile(loss=tf.keras.losses.CategoricalCrossentropy(),␣
 ↪metrics='accuracy', optimizer=tf.keras.optimizers.
 ↪Adam(learning_rate=learning_rate))
```

[ ]:
```
es = tf.keras.callbacks.EarlyStopping(monitor="val_loss", patience=5,␣
 ↪restore_best_weights=True,)
checkpointer = ModelCheckpoint(filepath='saved_models/
 ↪cnn_combined_classification.hdf5', verbose=1, save_best_only=True)

with tf.device('/device:GPU:0'):
  history = cnn_model.fit(Combined_training_data, training_onehot,␣
 ↪batch_size=batch_size, epochs=epochs,␣
 ↪validation_data=(Combined_validation_data, validation_onehot), callbacks=[es,␣
 ↪checkpointer], verbose=1)
```

```
Epoch 1/200
1046/1559 [====================>...] - ETA: 1:03 - loss: 1.6027 -
accuracy: 0.3464
```

```
[ ]: plot_model_history(history, 'CNN Model With Combined Feature Sapce')
model_scoring(cnn_model, history, Combined_testing_data, testing_pair_labels)
```

9.2 Reshaping data for RNN and LSTM models

```
[ ]: Combined_training_data, Combined_validation_data, Combined_testing_data =␣
 ↪reshape_data_for_rnn_lstm(Combined_training_data, Combined_validation_data,␣
 ↪Combined_testing_data)
```

```
[ ]: print('training data shape:', Combined_training_data.shape)
print('validation data shape:', Combined_validation_data.shape)
print('testing data shape:', Combined_testing_data.shape)
```

9.3 RNN Model

```
[ ]: learning_rate = 0.001
batch_size = 512
epochs = 200
```

```
[ ]: rnn_model = Sequential()
rnn_model.add(SimpleRNN(128, activation='relu'))
#rnn_model.add(Dropout(0.5))
rnn_model.add(Dense(10, activation='softmax'))
rnn_model.compile(loss=tf.keras.losses.CategoricalCrossentropy(),␣
 ↪metrics='accuracy', optimizer=tf.keras.optimizers.
 ↪Adam(learning_rate=learning_rate))
```

```
[ ]: es = tf.keras.callbacks.EarlyStopping(monitor="val_loss", patience=5,␣
 ↪restore_best_weights=True,)
checkpointer = ModelCheckpoint(filepath='saved_models/
 ↪rnn_combined_classification.hdf5', verbose=1, save_best_only=True)

with tf.device('/device:GPU:0'):
  history = rnn_model.fit(Combined_training_data, training_onehot,␣
 ↪batch_size=batch_size, epochs=epochs,␣
 ↪validation_data=(Combined_validation_data, validation_onehot), callbacks=[es,␣
 ↪checkpointer], verbose=1)
```

```
[ ]: plot_model_history(history, 'RNN Model With Combined Feature Sapce')
model_scoring(rnn_model, history, Combined_testing_data, testing_pair_labels)
```

9.4 LSTM Model

[ ]:
```
learning_rate = 0.001
batch_size = 512
epochs = 200
```

[ ]:
```
lstm_model = Sequential()
lstm_model.add(LSTM(256))
lstm_model.add(Dropout(0.2))
lstm_model.add(Dense(10, activation='softmax'))
lstm_model.compile(loss=tf.keras.losses.CategoricalCrossentropy(),␣
↪metrics='accuracy', optimizer=tf.keras.optimizers.
↪Adam(learning_rate=learning_rate))
```

[ ]:
```
es = tf.keras.callbacks.EarlyStopping(monitor="val_loss", patience=5,␣
↪restore_best_weights=True,)
checkpointer = ModelCheckpoint(filepath='saved_models/
↪lstm_combined_classification.hdf5', verbose=1, save_best_only=True)

with tf.device('/device:GPU:0'):
  history = lstm_model.fit(Combined_training_data, training_onehot,␣
↪batch_size=batch_size, epochs=epochs,␣
↪validation_data=(Combined_validation_data, validation_onehot), callbacks=[es,␣
↪checkpointer], verbose=1)
```

[ ]:
```
plot_model_history(history, 'LSTM Model With Combined Feature Sapce')
model_scoring(lstm_model, history, Combined_testing_data, testing_pair_labels)
```

[ ]:
```

```