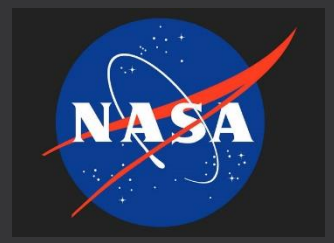

Design and Analysis of Convolutional Neural Network for RF Signal Modulation Classification for In-Orbit Deployment

Cognitive Communications for Aerospace Applications (CCAA) Workshop
June 21, 2021

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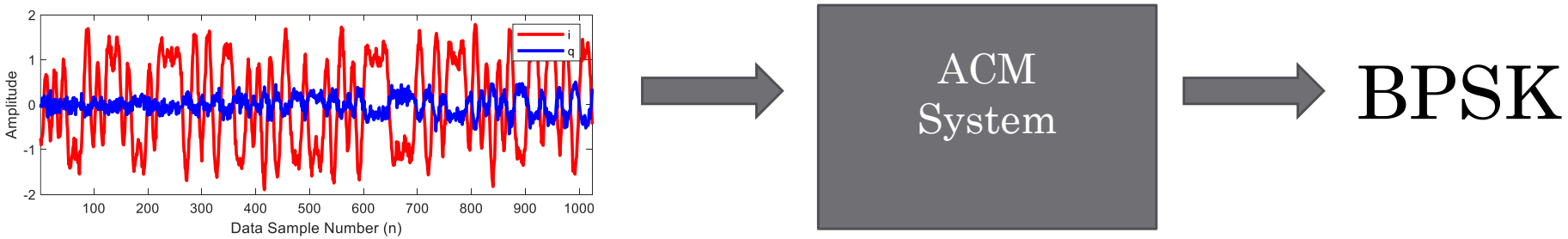
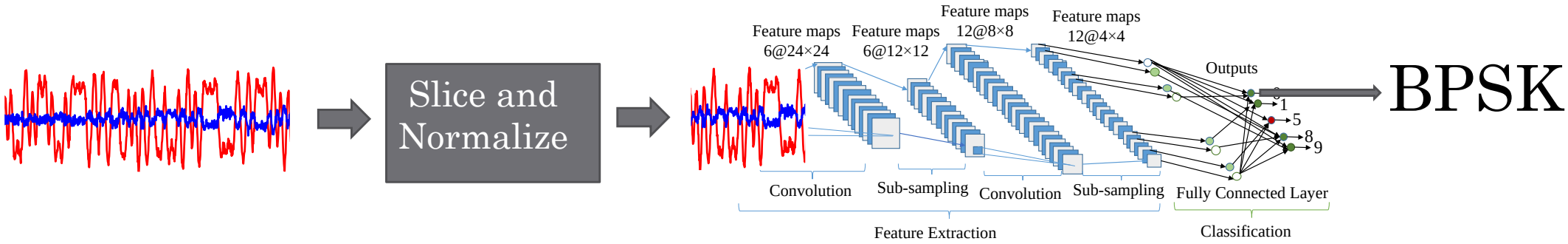
CNN for Automatic Modulation Classification

- Automatic signal modulation classification (AMC) is a major research direction of signal recognition.
- AMC is the automatic identification of the modulation format of the transmitted signals by observing the received data samples which are corrupted by the noise and fading channels.
- It is an intermediate operation between the signal detection and the data demodulation
- AMC plays an important role in civilian and military applications such as software-defined radio, cognitive radio, dynamic spectrum management, interference identification and electronic warfare.



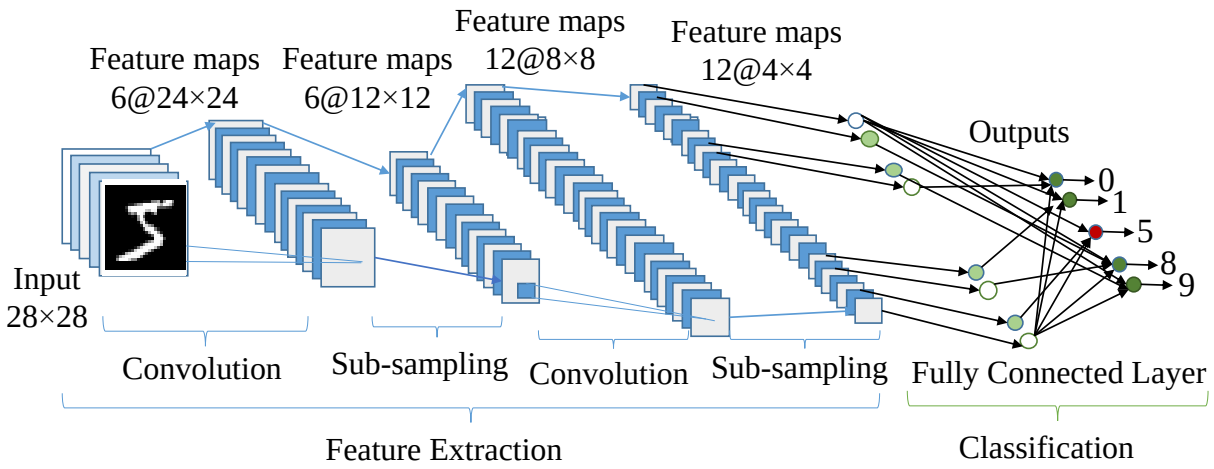
CNN for Automatic Modulation Classification

- Deep Learning (DL) has been described as a universal learning approach that is able to solve many types problems in different application domains.
- Our focus is on implementing a DL engine in space that would enable Automatic Modulation Classification (AMC) outside of Earth's atmosphere. Implementation of modulation recognition algorithm would allow for the deployment of real-time, high rate, low-power and useful neural network for RF communications.
- We explored a Convolutional Neural Network (CNN), and a Convolution Neural Network that Implements Transfer Learning (CNN-TL) for the successful classification of different modulation schemes for data transmission.
- The developed software was shown to successfully classify the modulation schemes using the open source Radio ML 2018 dataset.



CNN Algorithm

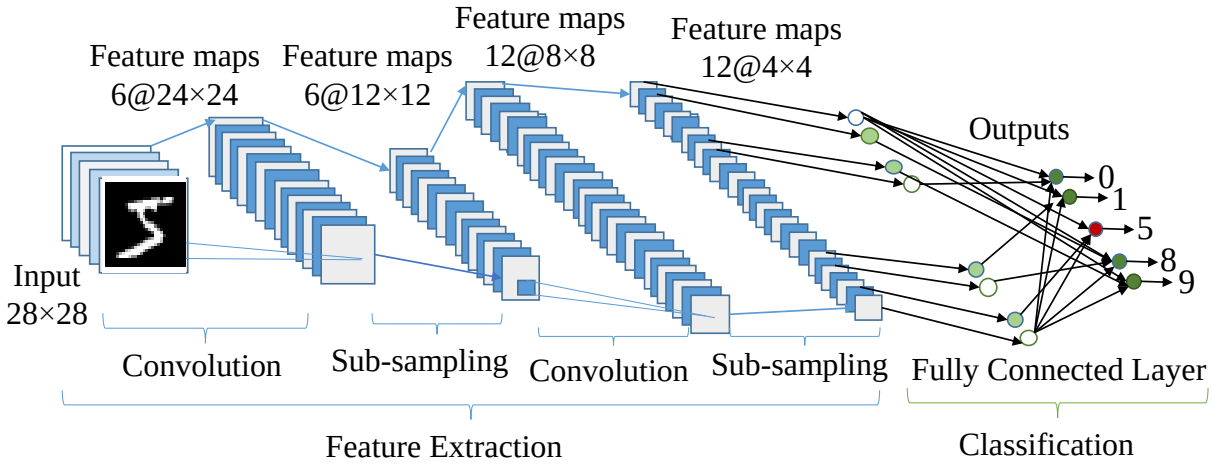
- Learns by extracting features from data samples using trainable convolution kernels (filters)
- Last layer is typical fully connected layer
- Very strong for image recognition and classification



Full CNN Training: All Layers are Optimized

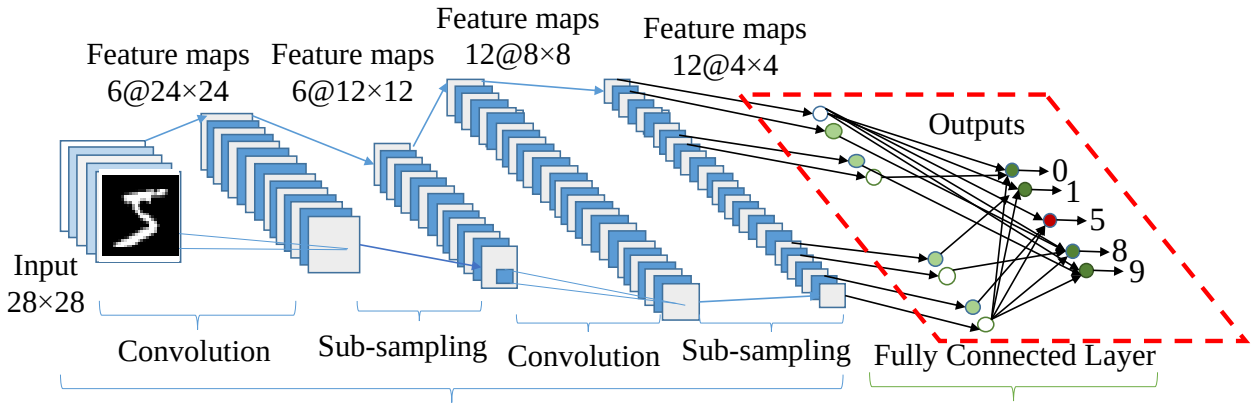
CNN for Transfer Learning

- Learns by extracting features from data samples using trainable convolution kernels (filters)
- Last layer is typical fully connected layer
- Very strong for image recognition and classification



Full CNN Training: All Layers are Optimized

- Transfer Learning
  - Pre-train the convolution part of the network
  - Train only the fully connected layer with new data
  - Much simpler to implement in hardware

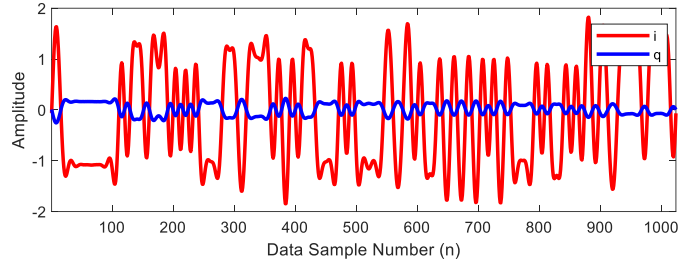


Radio ML Dataset

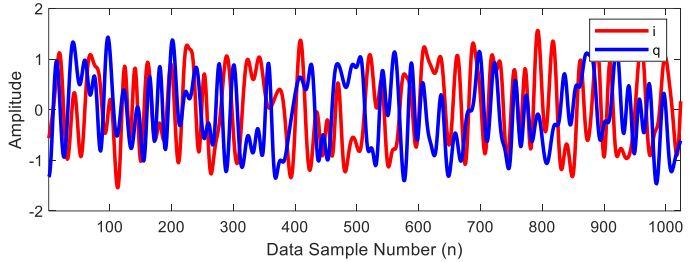
- Dataset used in this study
  - RadioML 2018
  - 24 Modulation Classes
  - SNR range: -20 to 30bB
- 4069 samples for each class in each SNR segment
- Sample size 2×1024 for CNN input
  - I channel
  - Q channel
- Little post processing within data
  - Cut sample lengths
  - Normalize to zero mean and unit variance

Class Number	Mod. Class
1	OOK
2	4ASK
3	8ASK
4	BPSK
5	QPSK
6	8PSK
7	16PSK
8	32PSK
9	16APSK
10	32APSK
11	64APSK
12	128APSK
13	16QAM
14	32QAM
15	64QAM
16	128QAM
17	256QAM
18	AM-SSB-WC
19	AM-SSB-SC
20	AM-DSB-WC
21	AM-DSB-SC
22	FM
23	GMSK
24	OQPSK

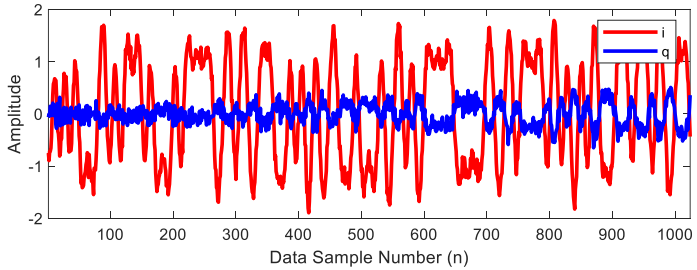
BPSK
30dB SNR



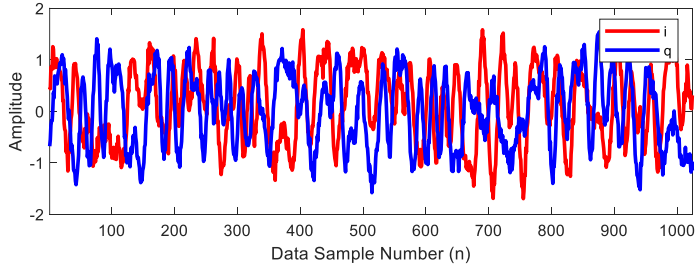
32PSK
30dB SNR



BPSK
8dB SNR



32PSK
8dB SNR



CNN Transfer Learning

- CNN used for transfer learning test
  - 2 convolution layers
  - 2 fully connected layers
- Dataset broken into two groups
  - Fully train on one set
  - Transfer learn the other set

```
----------------------------------------------------------------
        Layer (type)               Output Shape         Param #
================================================================
            Conv2d-1          [-1, 32, 1024, 1]           1,632
              ReLU-2          [-1, 32, 1024, 1]               0
         MaxPool2d-3           [-1, 32, 512, 1]               0
            Conv2d-4           [-1, 64, 512, 1]          51,264
              ReLU-5           [-1, 64, 512, 1]               0
         MaxPool2d-6           [-1, 64, 256, 1]               0
           Dropout-7                [-1, 16384]               0
            Linear-8                 [-1, 1000]      16,385,000
            Linear-9                   [-1, 24]          24,024
================================================================
Total params: 16,461,920
Trainable params: 16,461,920
Non-trainable params: 0
----------------------------------------------------------------
Input size (MB): 0.01
Forward/backward pass size (MB): 1.38
Params size (MB): 62.80
Estimated Total Size (MB): 64.19
----------------------------------------------------------------
```

	Class Number	Mod. Class
Transfer Set A	1	OOK
	2	4ASK
	3	8ASK
	4	BPSK
	5	QPSK
	6	8PSK
	7	16PSK
	8	32PSK
	9	16APSK
	10	32APSK
	11	64APSK
	12	128APSK
Transfer Set B	13	16QAM
	14	32QAM
	15	64QAM
	16	128QAM
	17	256QAM
	18	AM-SSB-WC
	19	AM-SSB-SC
	20	AM-DSB-WC
	21	AM-DSB-SC
	22	FM
	23	GMSK
	24	OQPSK

CNN Transfer Learning

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  - 2 convolution layers
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- Dataset broken into two groups
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```
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        Layer (type)               Output Shape         Param #
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            Conv2d-1          [-1, 32, 1024, 1]           1,632
              ReLU-2          [-1, 32, 1024, 1]               0
         MaxPool2d-3           [-1, 32, 512, 1]               0
            Conv2d-4           [-1, 64, 512, 1]          51,264
              ReLU-5           [-1, 64, 512, 1]               0
         MaxPool2d-6           [-1, 64, 256, 1]               0
           Dropout-7                [-1, 16384]               0
            Linear-8                 [-1, 1000]      16,385,000
            Linear-9                   [-1, 24]          24,024
================================================================
Total params: 16,461,920
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----------------------------------------------------------------
Input size (MB): 0.01
Forward/backward pass size (MB): 1.38
Params size (MB): 62.80
Estimated Total Size (MB): 64.19
----------------------------------------------------------------
```
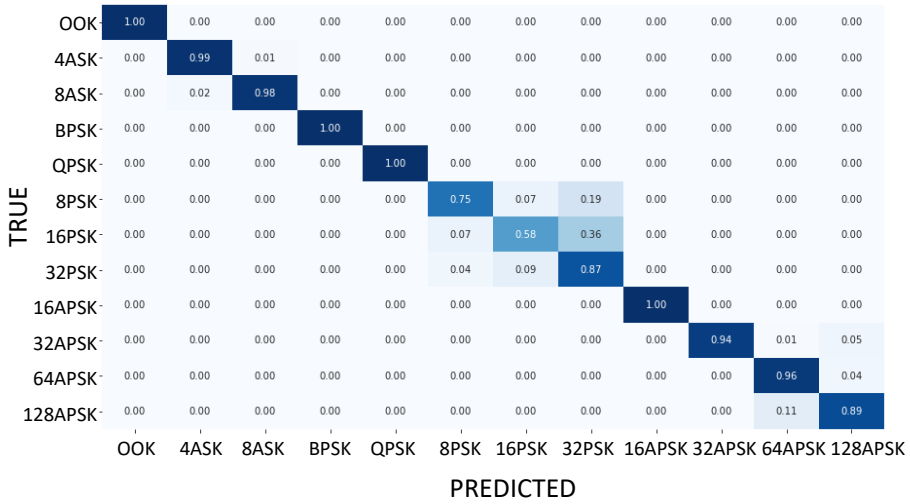
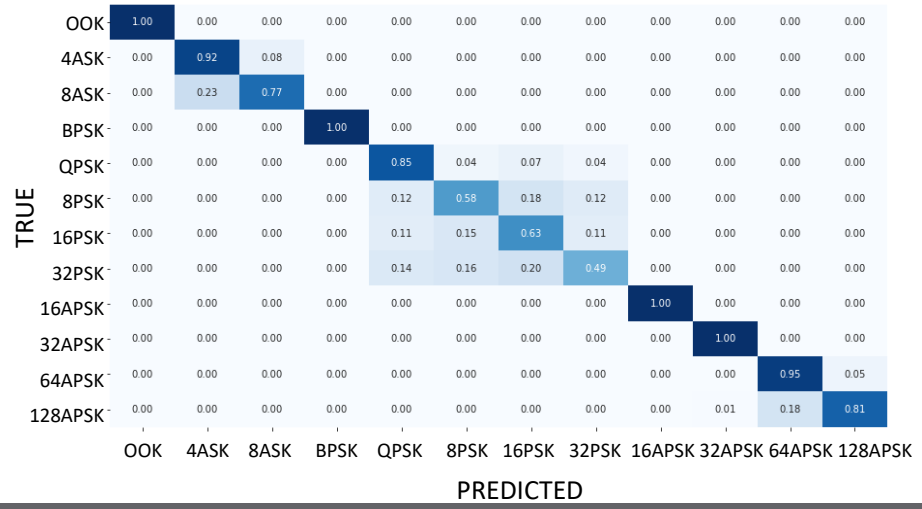

Learn Set A



Learn Set B, Transfer Learn Set A

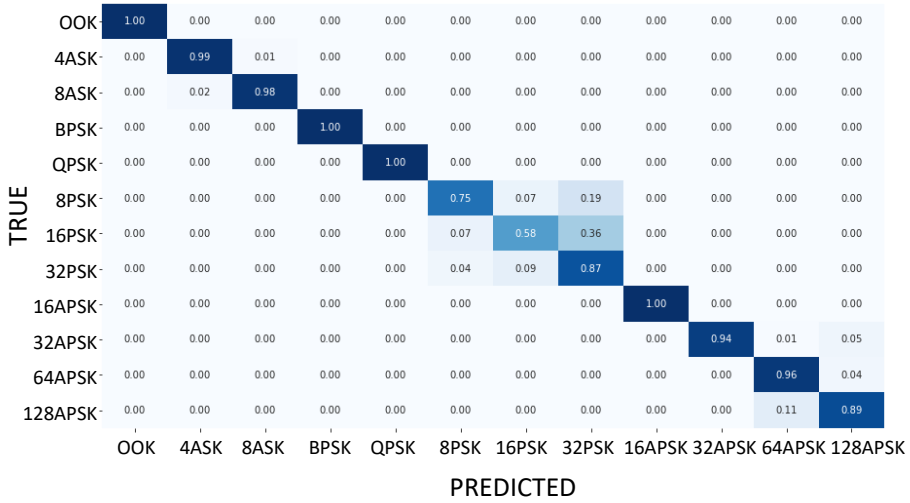


CNN Transfer Learning

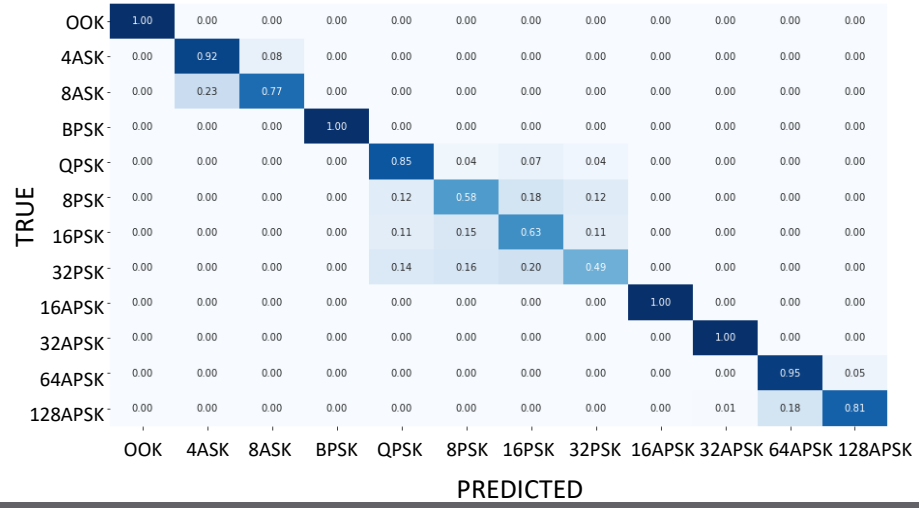
- CNN used for transfer learning test
  - 2 convolution layers
  - 2 fully connected layers
- Dataset broken into two groups
  - Fully train on one set
  - Transfer learn the other set

Metric	Train A (40 Epochs)	Train B (40 Epochs)	Train A Transfer B (40 + 40 Epochs)	Train B Transfer A (40 + 40 Epochs)
Accuracy	91.15%	80.40%	78.32%	83.34%

Learn Set A



Learn Set B, Transfer Learn Set A



CNN Optimization

- Deeper CNN
  - More convolution layers
  - More fully connected layers
  - Fewer parameters
  - Experiment is learning all 24 classes and testing using unique untrained data samples

Convolution Layers	Filter Size	FC Layers	Epochs	Parameters	Training Accuracy (%)	Testing Accuracy (%)
2→16→16→16	1 by 5	2048→250→24	40	521,042	82.0	74.8
	1 by 3		40	519,954	78.9	71.7
2→16→16→16→16→16	1 by 3	512→250→24	40	137,522	77.4	75.9
		512→128→24	40	72,008	71.4	70.28
2→16→16→16→16→16→16	1 by 3	256→128→24	40	40,024	76.7	75.6
			80	40,024	82.7	81.4
2→12→12→12→12→12→12	1 by 3	192→128→24	40	30,104	66.3	65.2
			80	30,104	75.7	74.8
2→12→12→12→12→12→12	1 by 3	192→64→24	80	16,216	77.8	76.5
			160	16,216	78.2	77.4
2→8→8→8→8→8→8	1 by 3	128→64→24	80	10,872	68.3	67.4
			160	10,872	72.5	71.7
2→8→8→8→8→8→8	1 by 3	128→24	160	4,152	54.6	54.06

CNN Optimization

- Range of CNN designs were evaluated to find tradeoff between number of parameters and accuracy
  - Two bold networks show strong accuracy vs. throughput results

Convolution Layers	Filter Size	FC Layers	Epochs	Parameters	Training Accuracy (%)	Testing Accuracy (%)
2→16→16→16	1 by 5	2048→250→24	40	521,042	82.0	74.8
	1 by 3		40	519,954	78.9	71.7
2→16→16→16→16→16	1 by 3	512→250→24	40	137,522	77.4	75.9
		512→128→24	40	72,008	71.4	70.28
2→16→16→16→16→16→16	**1 by 3**	**256→128→24**	**40**	**40,024**	**76.7**	**75.6**
			80	**40,024**	**82.7**	**81.4**
2→12→12→12→12→12→12	1 by 3	192→128→24	40	30,104	66.3	65.2
			80	30,104	75.7	74.8
2→12→12→12→12→12→12	**1 by 3**	**192→64→24**	**80**	**16,216**	**77.8**	**76.5**
			160	**16,216**	**78.2**	**77.4**
2→8→8→8→8→8→8	1 by 3	128→64→24	80	10,872	68.3	67.4
			160	10,872	72.5	71.7
2→8→8→8→8→8→8	1 by 3	128→24	160	4,152	54.6	54.06

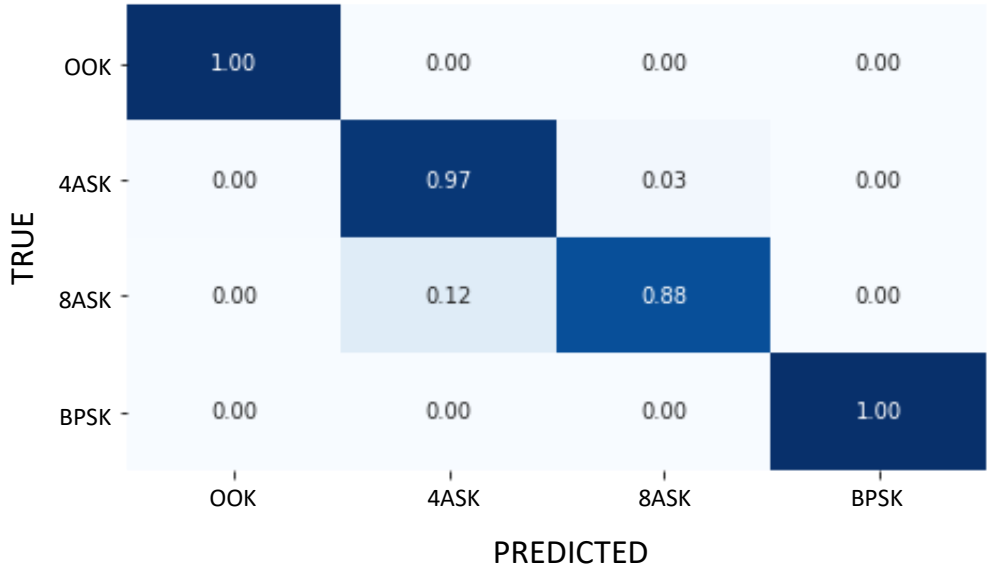
CNN Optimization

- Deeper CNN
  - 6 convolution layers
  - 2 fully connected layers
  - More layers and fewer parameters

```
----------------------------------------------------------------
        Layer (type)               Output Shape         Param #
================================================================
            Conv2d-1         [-1, 12, 1024, 1]              72
              ReLU-2         [-1, 12, 1024, 1]               0
         MaxPool2d-3          [-1, 12, 512, 1]               0
            Conv2d-4          [-1, 12, 512, 1]             432
              ReLU-5          [-1, 12, 512, 1]               0
         MaxPool2d-6          [-1, 12, 256, 1]               0
            Conv2d-7          [-1, 12, 256, 1]             432
              ReLU-8          [-1, 12, 256, 1]               0
         MaxPool2d-9          [-1, 12, 128, 1]               0
           Conv2d-10          [-1, 12, 128, 1]             432
             ReLU-11          [-1, 12, 128, 1]               0
        MaxPool2d-12           [-1, 12, 64, 1]               0
           Conv2d-13           [-1, 12, 64, 1]             432
             ReLU-14           [-1, 12, 64, 1]               0
        MaxPool2d-15           [-1, 12, 32, 1]               0
           Conv2d-16           [-1, 12, 32, 1]             432
             ReLU-17           [-1, 12, 32, 1]               0
        MaxPool2d-18           [-1, 12, 16, 1]               0
          Dropout-19                 [-1, 192]               0
           Linear-20                  [-1, 64]          12,288
           Linear-21                  [-1, 12]             768
================================================================
Total params: 15,288
Trainable params: 15,288
Non-trainable params: 0
----------------------------------------------------------------
Input size (MB): 0.01
Forward/backward pass size (MB): 0.46
Params size (MB): 0.06
Estimated Total Size (MB): 0.53
----------------------------------------------------------------
```

Optimized CNN Transfer Learning

- Transfer Learning to Add Class
  - Step 1: Train CNN to learn 4 modulation types




```
----------------------------------------------------------------
        Layer (type)               Output Shape         Param #
================================================================
            Conv2d-1          [-1, 12, 1024, 1]              72
              ReLU-2          [-1, 12, 1024, 1]               0
         MaxPool2d-3           [-1, 12, 512, 1]               0
            Conv2d-4           [-1, 12, 512, 1]             432
              ReLU-5           [-1, 12, 512, 1]               0
         MaxPool2d-6           [-1, 12, 256, 1]               0
            Conv2d-7           [-1, 12, 256, 1]             432
              ReLU-8           [-1, 12, 256, 1]               0
         MaxPool2d-9           [-1, 12, 128, 1]               0
           Conv2d-10           [-1, 12, 128, 1]             432
             ReLU-11           [-1, 12, 128, 1]               0
        MaxPool2d-12            [-1, 12, 64, 1]               0
           Conv2d-13            [-1, 12, 64, 1]             432
             ReLU-14            [-1, 12, 64, 1]               0
        MaxPool2d-15            [-1, 12, 32, 1]               0
           Conv2d-16            [-1, 12, 32, 1]             432
             ReLU-17            [-1, 12, 32, 1]               0
        MaxPool2d-18            [-1, 12, 16, 1]               0
          Dropout-19                  [-1, 192]               0
           Linear-20                   [-1, 64]          12,288
           Linear-21                   [-1, 12]             768
================================================================
Total params: 15,288
Trainable params: 15,288
Non-trainable params: 0
----------------------------------------------------------------
Input size (MB): 0.01
Forward/backward pass size (MB): 0.46
Params size (MB): 0.06
Estimated Total Size (MB): 0.53
----------------------------------------------------------------
```

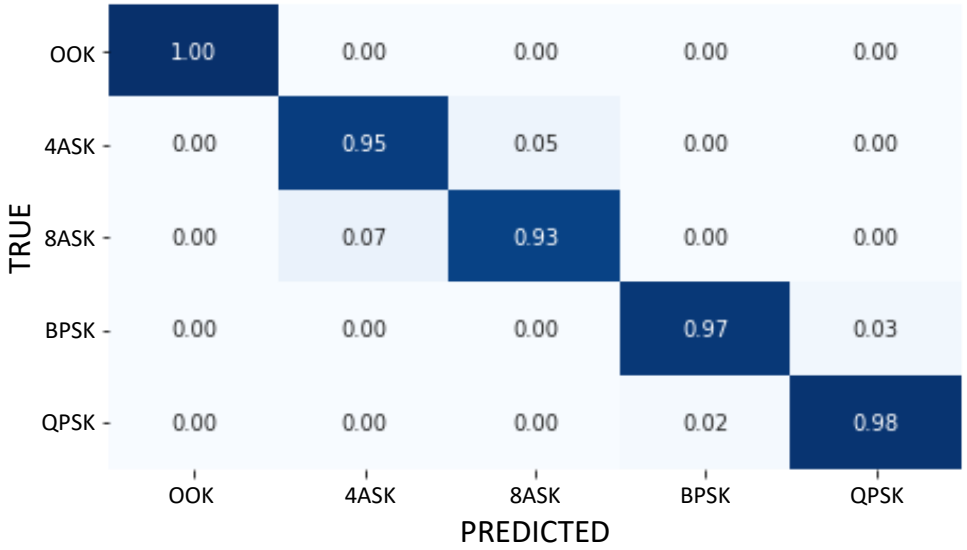
Optimized CNN Transfer Learning

- Transfer Learning to Add Class
  - Step 2: Test with 4 learned modulations in addition to a new unlearned class


```
----------------------------------------------------------------
        Layer (type)               Output Shape         Param #
================================================================
            Conv2d-1          [-1, 12, 1024, 1]              72
              ReLU-2          [-1, 12, 1024, 1]               0
         MaxPool2d-3           [-1, 12, 512, 1]               0
            Conv2d-4           [-1, 12, 512, 1]             432
              ReLU-5           [-1, 12, 512, 1]               0
         MaxPool2d-6           [-1, 12, 256, 1]               0
            Conv2d-7           [-1, 12, 256, 1]             432
              ReLU-8           [-1, 12, 256, 1]               0
         MaxPool2d-9           [-1, 12, 128, 1]               0
           Conv2d-10           [-1, 12, 128, 1]             432
             ReLU-11           [-1, 12, 128, 1]               0
        MaxPool2d-12            [-1, 12, 64, 1]               0
           Conv2d-13            [-1, 12, 64, 1]             432
             ReLU-14            [-1, 12, 64, 1]               0
        MaxPool2d-15            [-1, 12, 32, 1]               0
           Conv2d-16            [-1, 12, 32, 1]             432
             ReLU-17            [-1, 12, 32, 1]               0
        MaxPool2d-18            [-1, 12, 16, 1]               0
          Dropout-19                  [-1, 192]               0
           Linear-20                   [-1, 64]          12,288
           Linear-21                   [-1, 12]             768
================================================================
Total params: 15,288
Trainable params: 15,288
Non-trainable params: 0
----------------------------------------------------------------
Input size (MB): 0.01
Forward/backward pass size (MB): 0.46
Params size (MB): 0.06
Estimated Total Size (MB): 0.53
----------------------------------------------------------------
```

Optimized CNN Transfer Learning

- Transfer Learning to Add Class
  - Step 3: Use transfer learning to train only the fully connected layers
  - Step 4: Test if the network is able to learn all 5 modulations



Training Here

```
----------------------------------------------------------------
        Layer (type)               Output Shape         Param #
================================================================
            Conv2d-1          [-1, 12, 1024, 1]              72
              ReLU-2          [-1, 12, 1024, 1]               0
         MaxPool2d-3           [-1, 12, 512, 1]               0
            Conv2d-4           [-1, 12, 512, 1]             432
              ReLU-5           [-1, 12, 512, 1]               0
         MaxPool2d-6           [-1, 12, 256, 1]               0
            Conv2d-7           [-1, 12, 256, 1]             432
              ReLU-8           [-1, 12, 256, 1]               0
         MaxPool2d-9           [-1, 12, 128, 1]               0
           Conv2d-10           [-1, 12, 128, 1]             432
             ReLU-11           [-1, 12, 128, 1]               0
        MaxPool2d-12            [-1, 12, 64, 1]               0
           Conv2d-13            [-1, 12, 64, 1]             432
             ReLU-14            [-1, 12, 64, 1]               0
        MaxPool2d-15            [-1, 12, 32, 1]               0
           Conv2d-16            [-1, 12, 32, 1]             432
             ReLU-17            [-1, 12, 32, 1]               0
        MaxPool2d-18            [-1, 12, 16, 1]               0
          Dropout-19                  [-1, 192]               0
           Linear-20                   [-1, 64]          12,288
           Linear-21                   [-1, 12]             768
================================================================
Total params: 15,288
Trainable params: 15,288
Non-trainable params: 0
----------------------------------------------------------------
Input size (MB): 0.01
Forward/backward pass size (MB): 0.46
Params size (MB): 0.06
Estimated Total Size (MB): 0.53
----------------------------------------------------------------
```

Conclusion and Future Work

- Summary
  - CNN for AMC
  - Low power deployment of signal modulation classification
    - Through CNN optimization
  - Transfer learning makes system adaptable
    - Also reduces complexity of training if deployed on custom hardware
- Future Work
  - Hardware Survey
    - Best options for low SWaP deployment
    - Algorithm refinement
      - Optimize throughput and classification accuracy
    - Dataset improvement
      - Generate custom dataset using SDR for real world examination