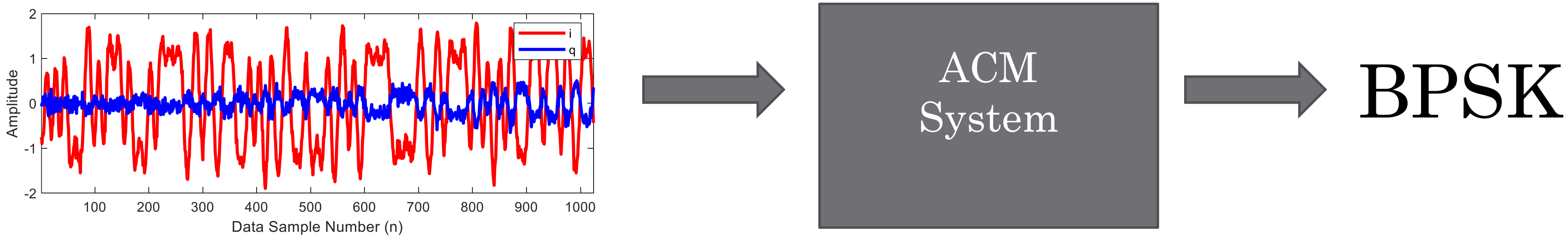
Design and Analysis of Convolutional Neural Network for RF Signal Modulation Classification for In-Orbit Deployment

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

Chris Yakopcic (Prixarc), Tarek M. Taha (Brisk), Sanjeevi Sirisha Karri (Prixarc), Guru Subramanyam (Prixarc), Aaron D. Smith (NASA Glenn), Janette C. Briones (NASA Glenn)

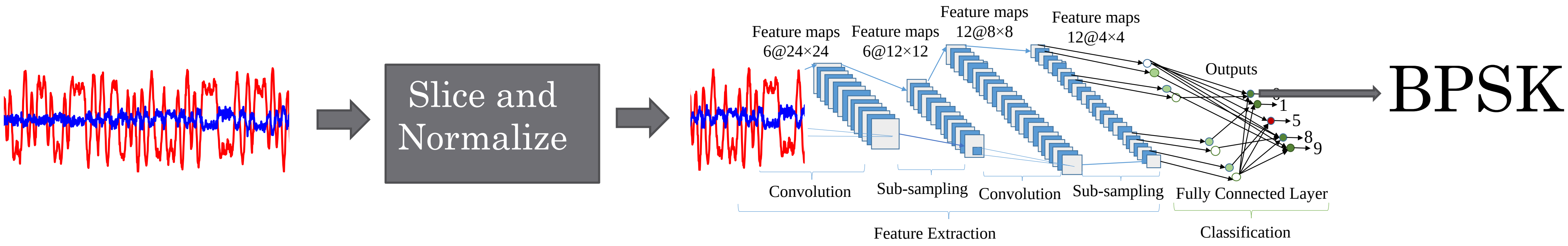
CNN for Automatic Modulation Classification

- 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.



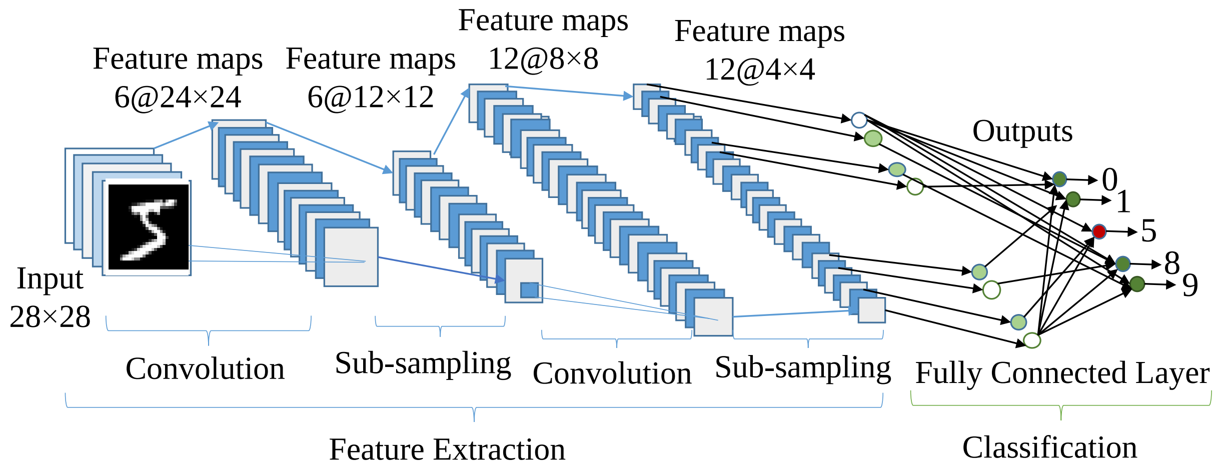
CNN for Automatic Modulation Classification

- 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

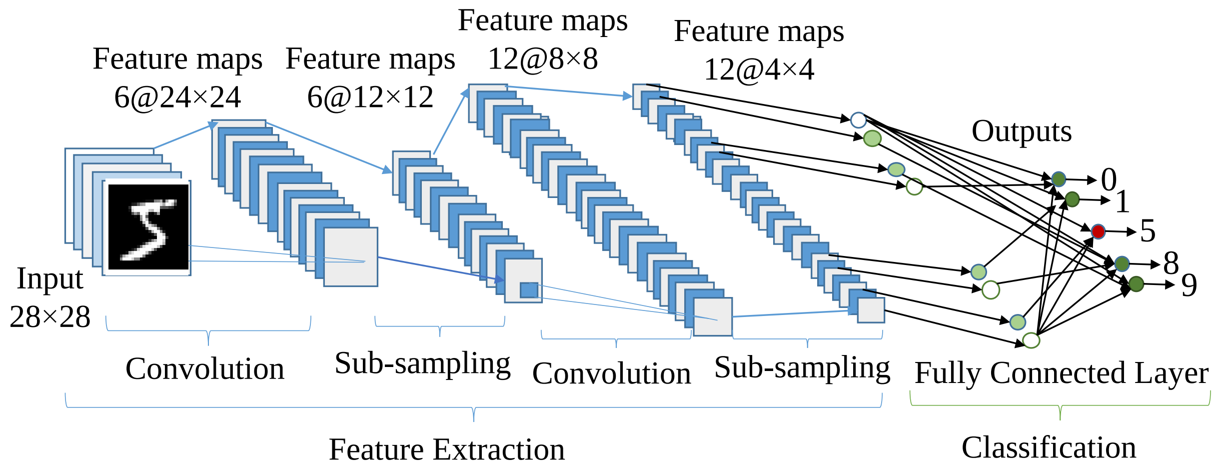
- Learns by extracting features from data samples using trainable convolution kernels (filters)
- Last layer is typical fully connected layer
- Very strong for image recognition and classification



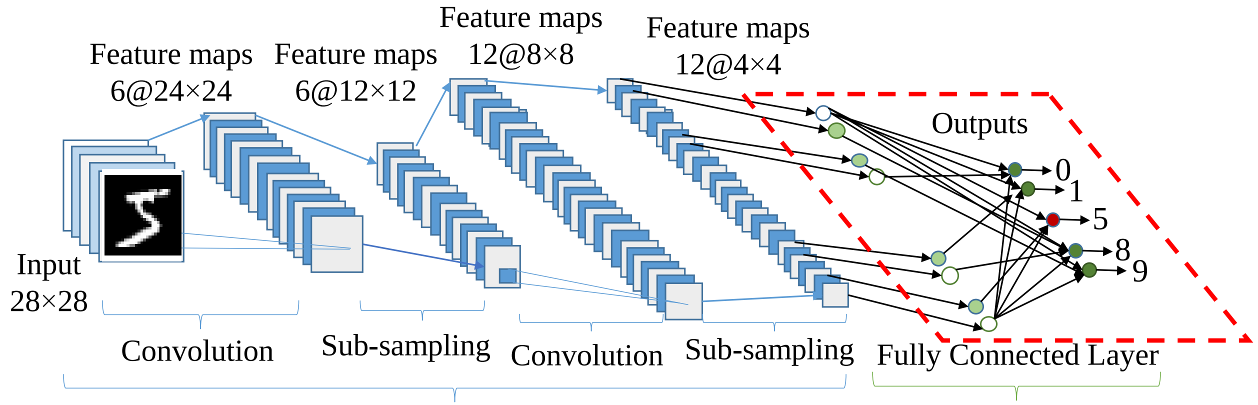
Full CNN Training: All Layers are Optimized

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
- 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



Full CNN Training: All Layers are Optimized



Pre-trained Layers

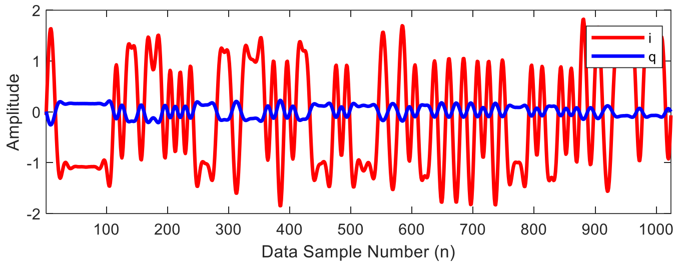
Transfer Layers
(Learning Occurs Here)

Radio ML Dataset

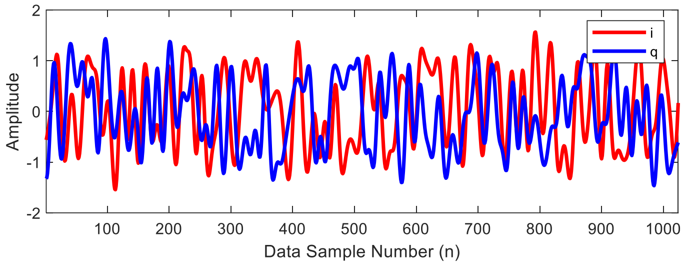
- Dataset used in this study
  - RadioML 2018
  - 24 Modulation Classes
  - SNR range: -20 to 30bB
- 4069 samples for each class in each SNR segment
- Sample size 2×1024 for CNN input
  - I channel
  - Q channel
- Little post processing within data
  - Cut sample lengths
  - Normalize to zero mean and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

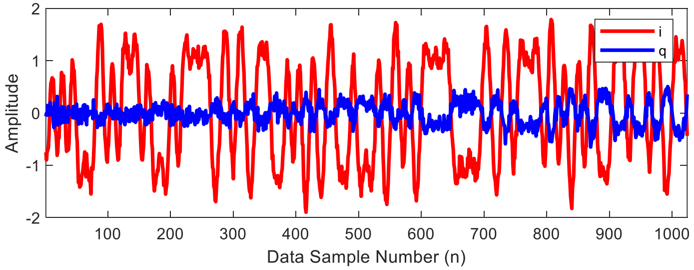
BPSK
30dB SNR



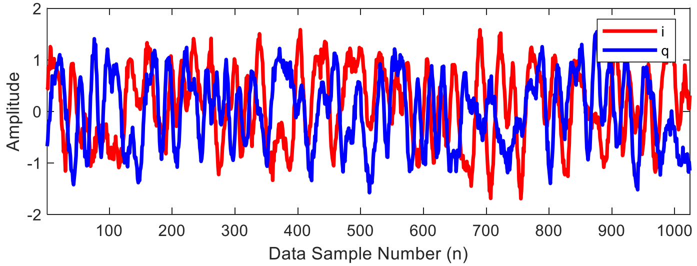
32PSK
30dB SNR



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
----------------------------------------------------------------
```

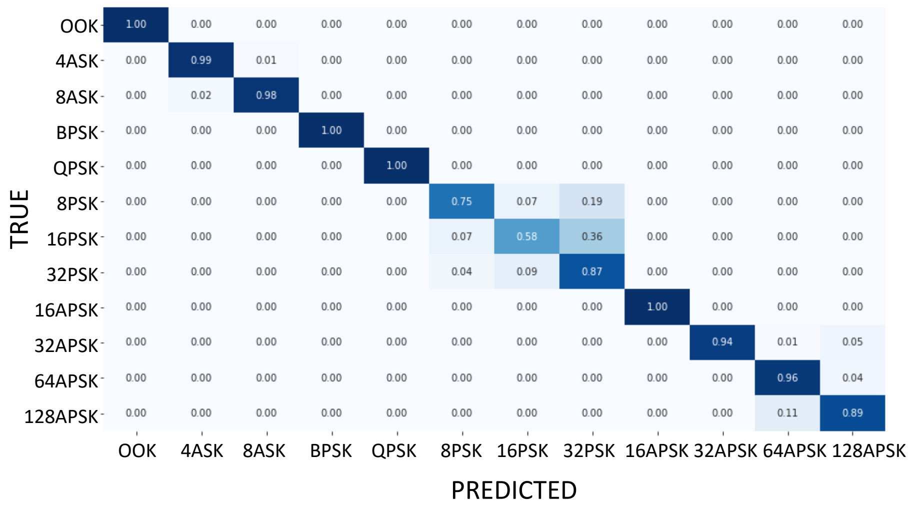
Transfer Set	Class Number	Mod. Class
Transfer Set A	1	OOK
	2	4ASK
	3	8ASK
	4	BPSK
	5	QPSK
	6	8PSK
	7	16PSK
	8	32PSK
	9	16APSK
	10	32APSK
	11	64APSK
	12	128APSK
Transfer Set B	13	16QAM
	14	32QAM
	15	64QAM
	16	128QAM
	17	256QAM
	18	AM-SSB-WC
	19	AM-SSB-SC
	20	AM-DSB-WC
	21	AM-DSB-SC
	22	FM
	23	GMSK
	24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

CNN Transfer Learning

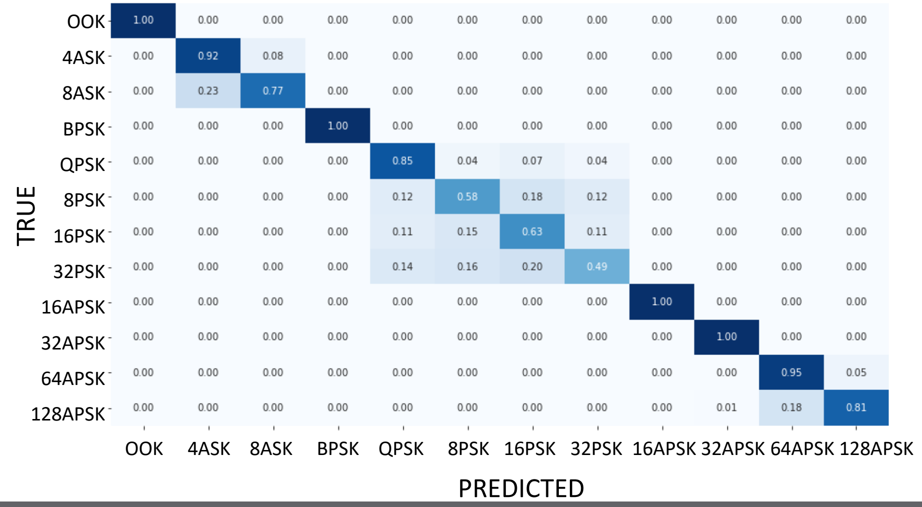
- CNN used for transfer learning test
  - 2 convolution layers
  - 2 fully connected layers
- Dataset broken into two groups
  - Fully train on one set
  - Transfer learn the other set

```
----------------------------------------------------------------
        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
----------------------------------------------------------------
```

Learn Set A



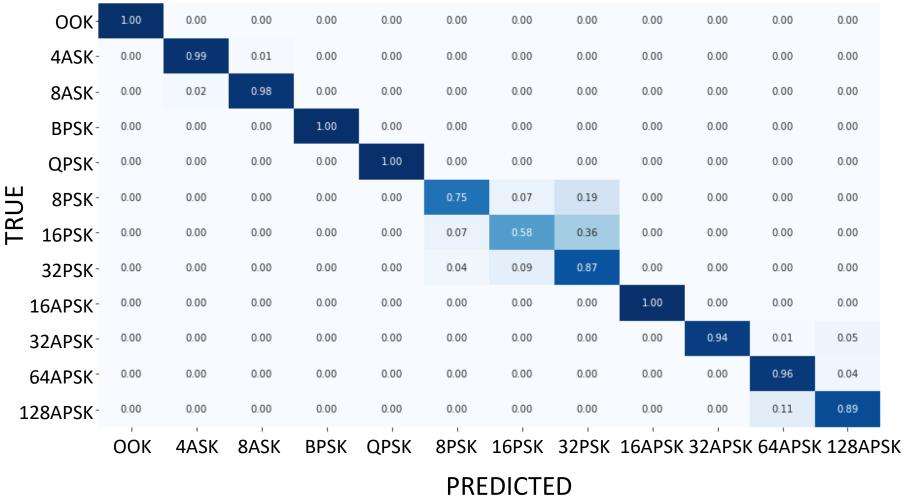
Learn Set B, Transfer Learn Set A



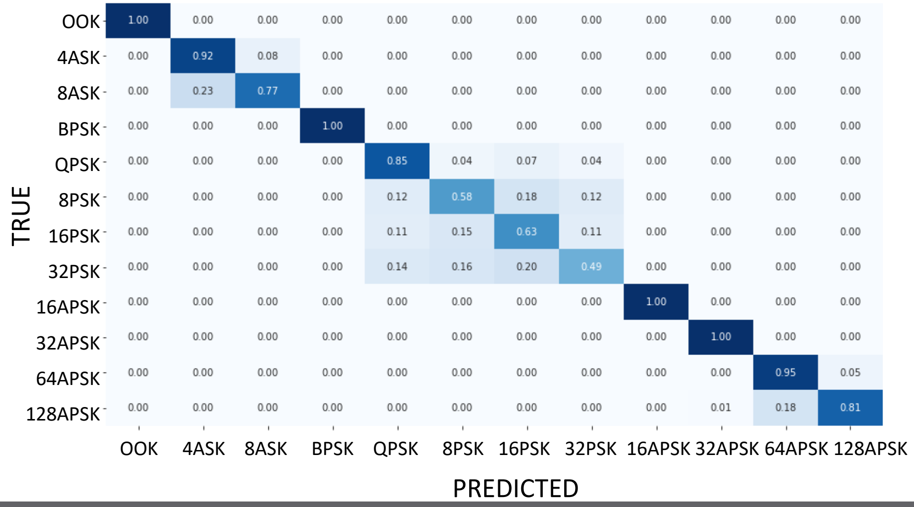
CNN Transfer Learning

- 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

Learn Set A



Learn Set B, Transfer Learn Set A



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%

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
----------------------------------------------------------------
```

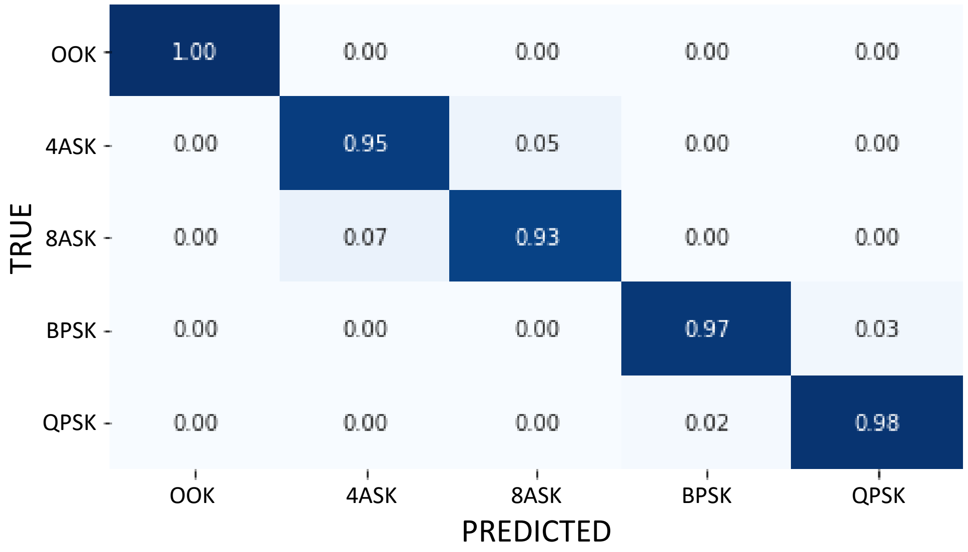
Optimized CNN Transfer Learning

- 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