Machine Learning Methods for Communication Networks and Systems – 051911

Francesco Musumeci

Dipartimento di Elettronica, Informazione e Bioingegneria (DEIB)

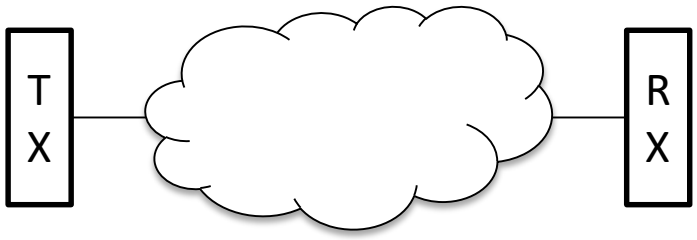
Politecnico di Milano, Milano, Italy

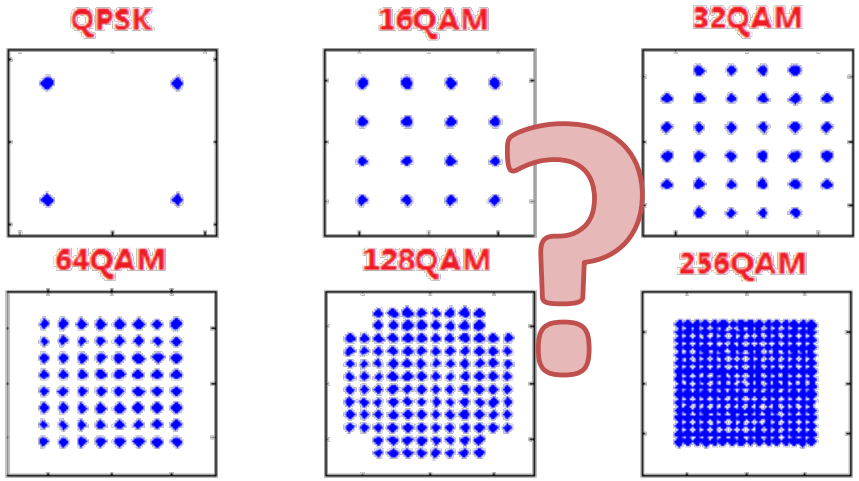
Part II – 5: Modulation format recognition

Physical layer domain

Modulation format recognition

- Current optical transmitters/receivers are able to operate at different MFs simultaneously
- Automatic MFR
  - Allows MF-dependent digital signal processing and OPM
  - Enables adaptive and dynamically changing MF Tx/Rx





- Traditional MFR requires prior information exchange between end points
  - additional delay for signal detection
- ML enables recognizing MF directly from features of the received signal

Modulation format recognition

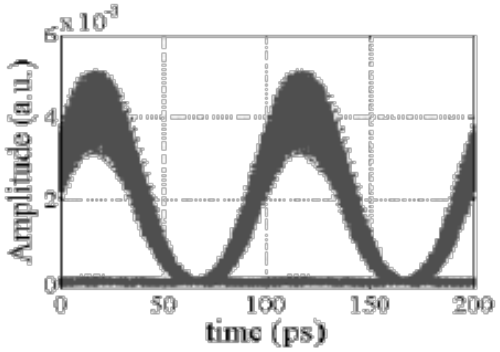
Source 1

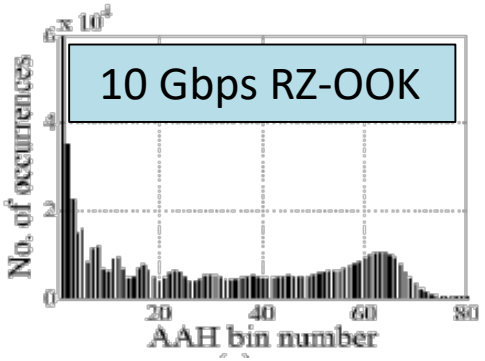
- Khan *et al.*, "Modulation format identification in heterogeneous fiber-optic networks using artificial neural networks", *Optics Express*, vol. 20 n. 11, May 2012
- Paper objective: recognize modulation format in optical fiber system
  - input
    - Asynchronous Amplitude Histograms (AAHs) of optical signal
  - output
    - Modulation Format
  - ML algorithm: Multi Layer Perceptron (MLP)… a Neural Network

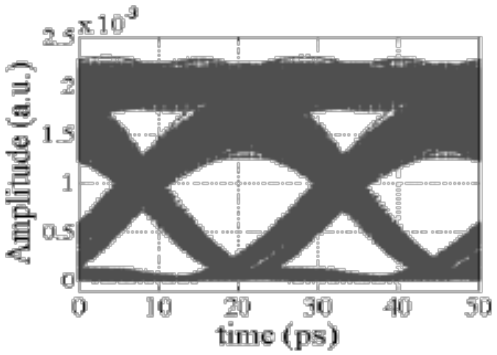
Modulation format recognition

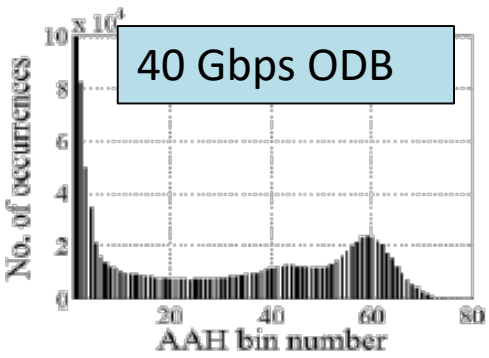
Source 1

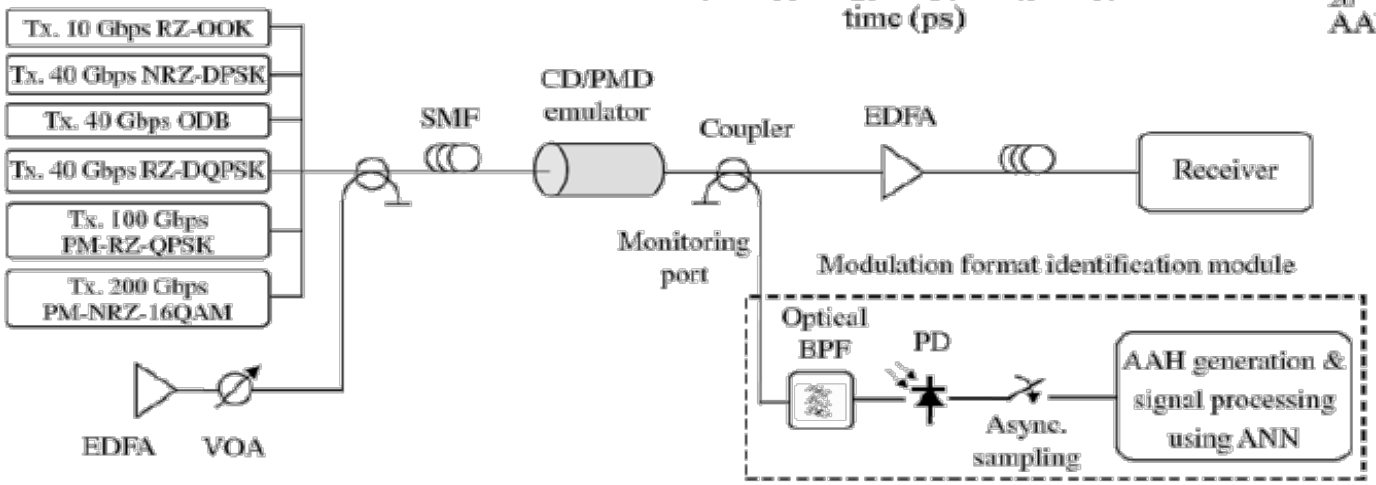
- Different MFs lead to different pulse shapes (eye-diagrams) and AAHs
  - AAHs do not require synchronized sampling
- AAHs are also affected by CD/PMD/OSNR
  - MFR should be performed independently







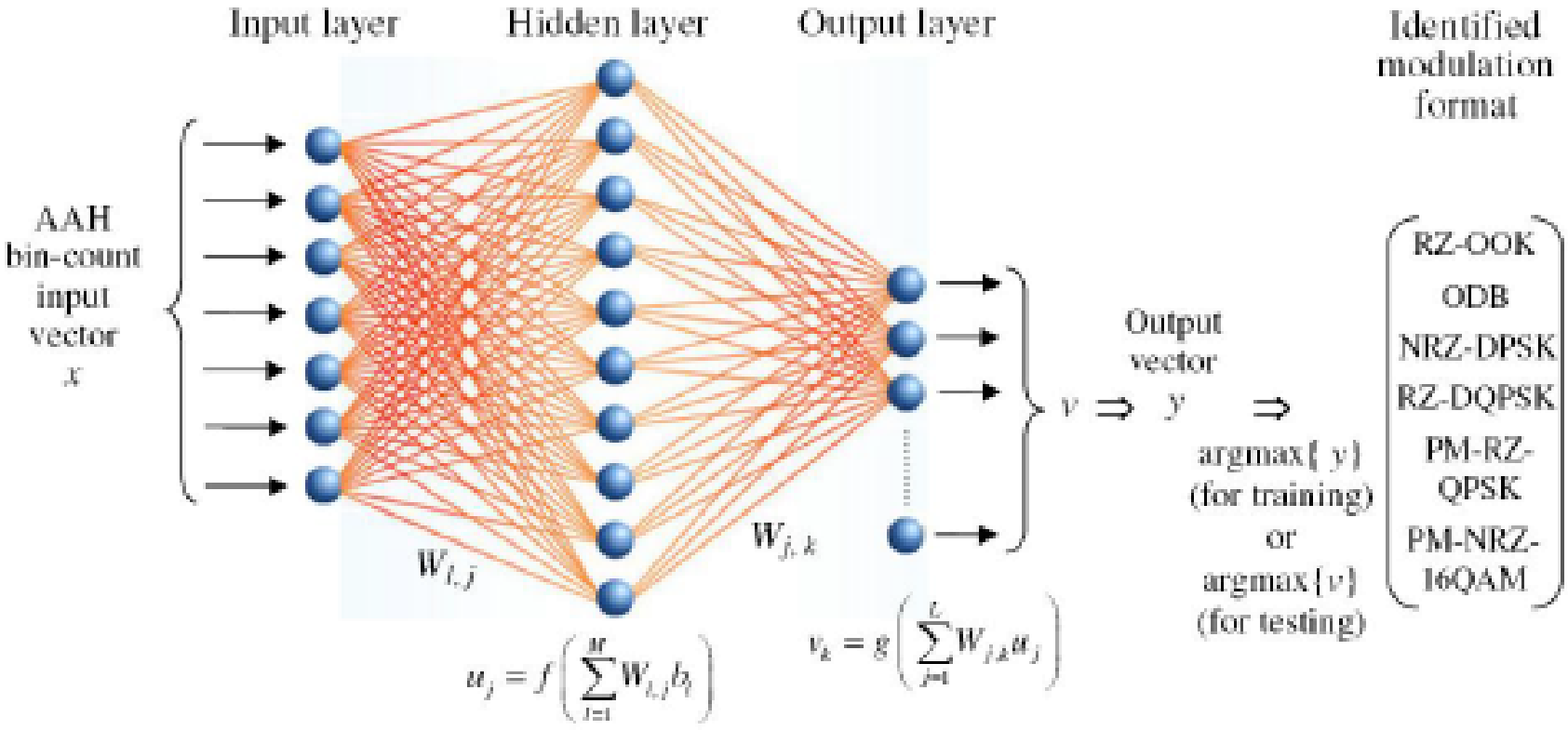




Modulation format recognition

Source 1

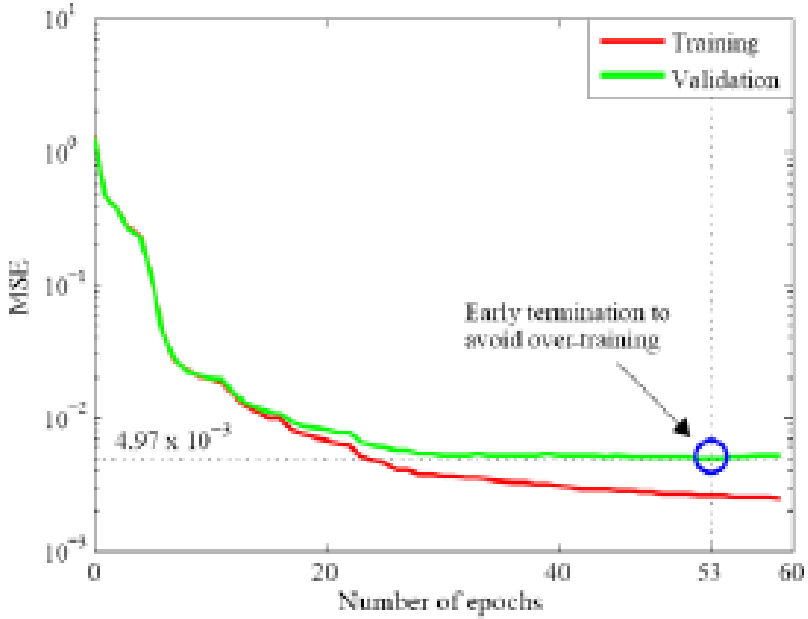
- Single hidden layer
  - nr of hidden nodes chosen by iteratively adding one node and checking MSE
  - Tanh (hidden layer) + sigmoid (output layer) activation functions

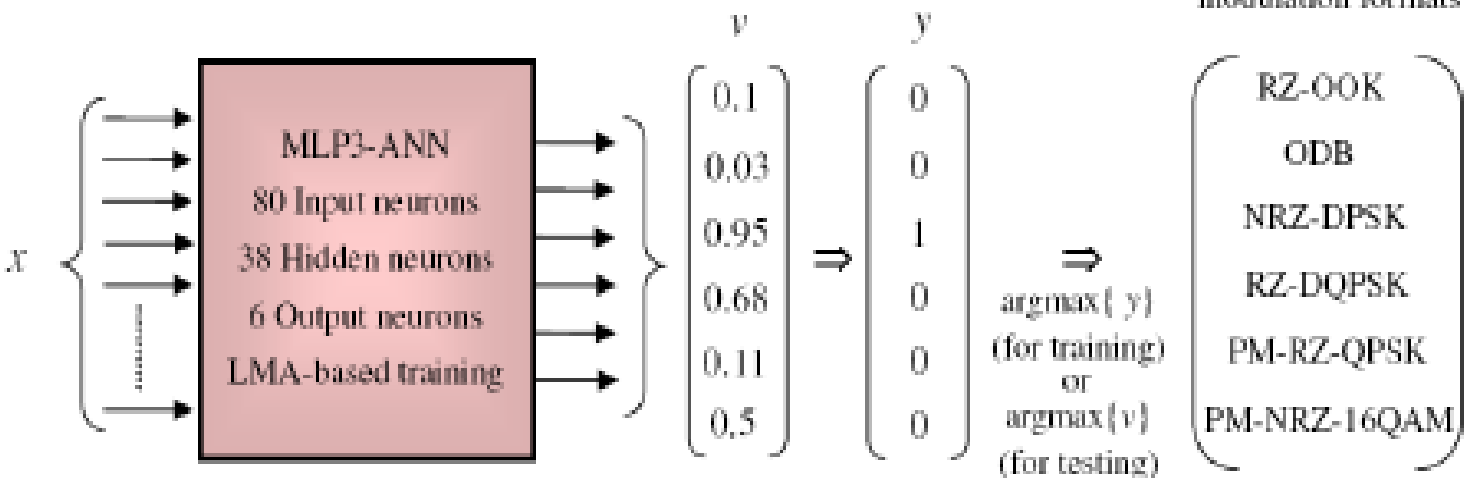


Modulation format recognition

Source 1

- Dataset with 26208 (x,y) pairs (AAHs, MF)
  - Changing MF, OSNR, CD, PMD
  - Training-validation-test sets: 56% - 19% - 25%
- Error backpropagation stopped at a predefined MSE threshold on the validation set (early stopping)



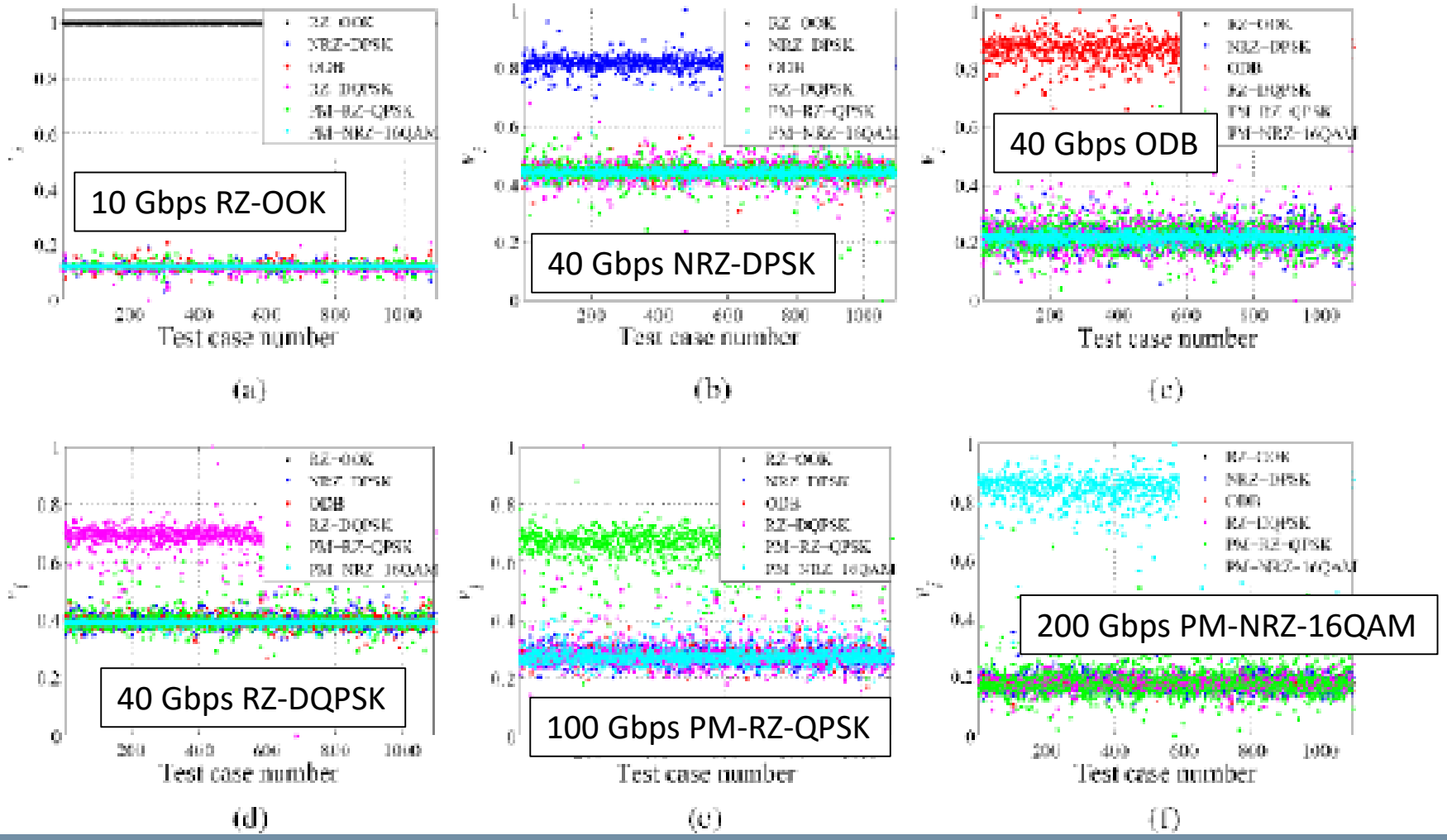


*LMA (Levenberg-Marquardt algorithm) is the weights update rule in error backpropagation

Modulation format recognition

Source 1

- MFR results: values of vector *v* for all MFs



Modulation format recognition

Source 1

- MFR results: confusion matrix
  - overall MFR accuracy 99.06%

Actual Modulation Format	Identified Modulation Format					
	RZ-OOK	NRZ-DPSK	ODB	RZ-DQPSK	PM-RZ-QPSK	PM-NRZ-16QAM
RZ-OOK	100%	-	-	-	-	-
NRZ-DPSK	-	99.81%	-	0.18%	-	-
ODB	-	-	99.9%	-	-	-
RZ-DQPSK	-	0.09%	-	97.98%	2.47%	-
PM-RZ-QPSK	-	-	-	1.83%	97.34%	0.64%
PM-NRZ-16QAM	-	0.09%	0.09%	-	0.18%	99.35%

Modulation format recognition

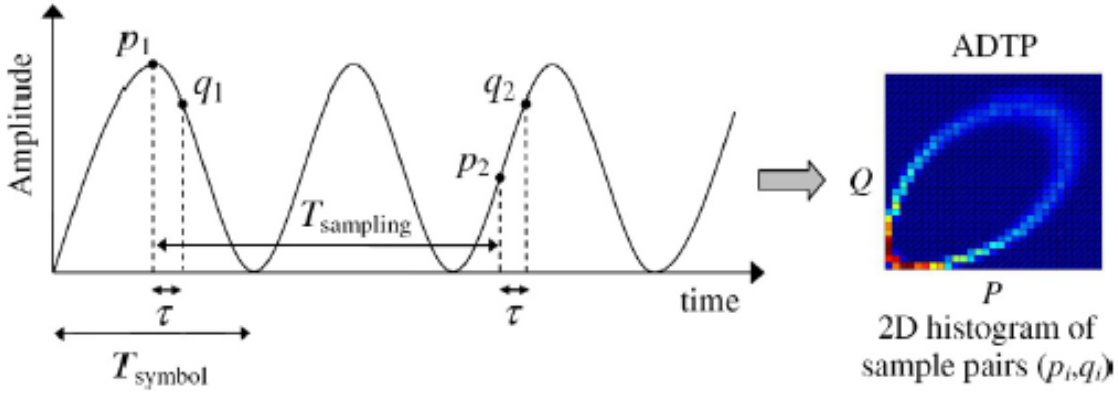
Source 2

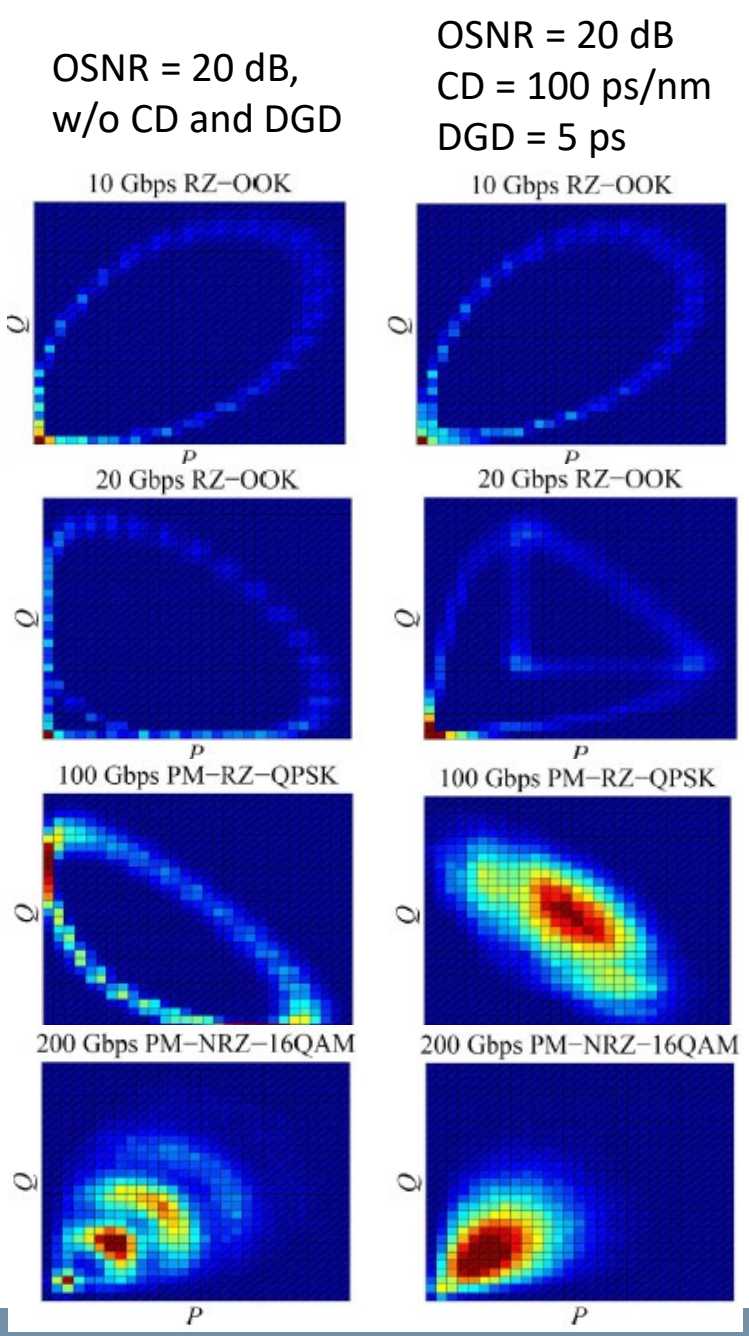
- Khan *et al.*, “Non-data-aided joint bit-rate and modulation format identification for next-generation heterogeneous optical networks”, *Optical Fiber Technology*, vol. 20 n. 2, Mar. 2014
- Paper objective: recognize modulation format and signal bit rate in optical fiber system
  - input
    - Asynchronous Delay-Tap Plots (ADTPs) of optical signal
  - output
    - Modulation Format
  - ML algorithm: Neural Network

Modulation format recognition

Source 2

- AAHs are not able to capture timing/slope information
  - it is hard to distinguish between different bit rates signals with same MF
- Solution: Asynchronous Delay-Tap Plots (ADTPs)
  - Essentially, they are joint probability distributions of closely-located samples

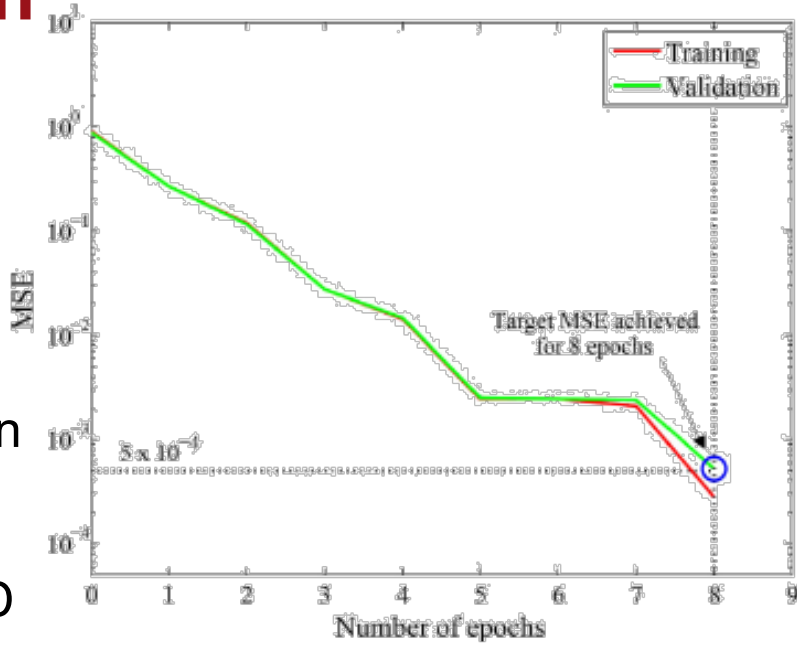


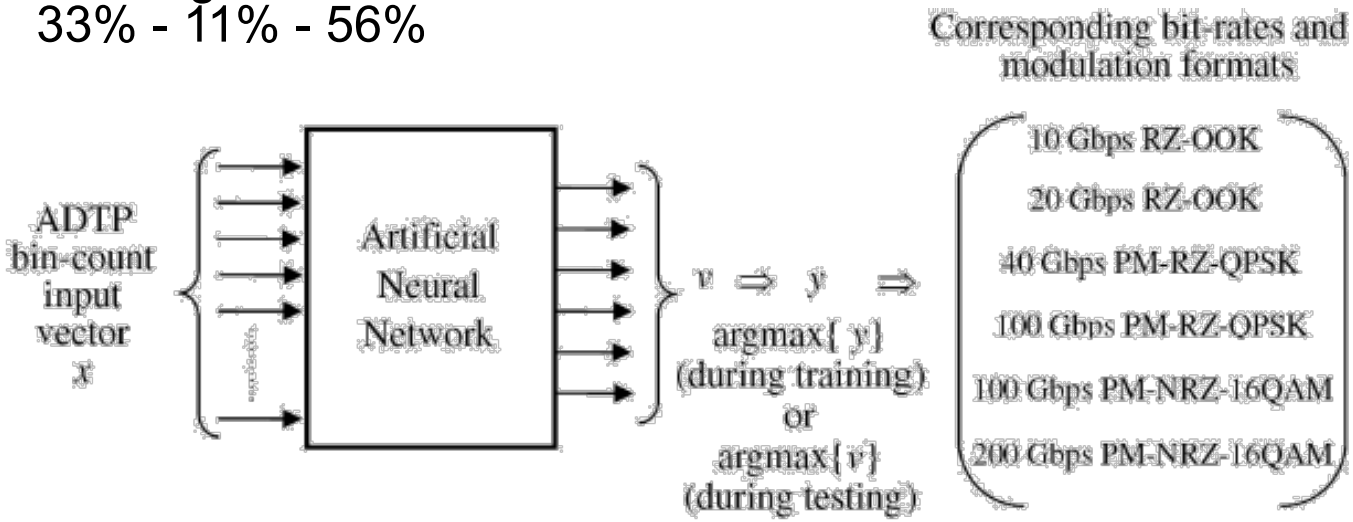


Modulation format recognition

Source 2

- NN with 16 hidden nodes
  - chosen via iterative increse of nodes number until MSE decreases
  - Tangent+sigmoid activation functions
- Error backpropagation stopped at a predefined MSE threshold on the validation set (early stopping)
- Dataset with 14976 ADTPs
  - Changing bit rate MF, OSNR, CD, DGD
  - Training-validation-test sets: 33% - 11% - 56%

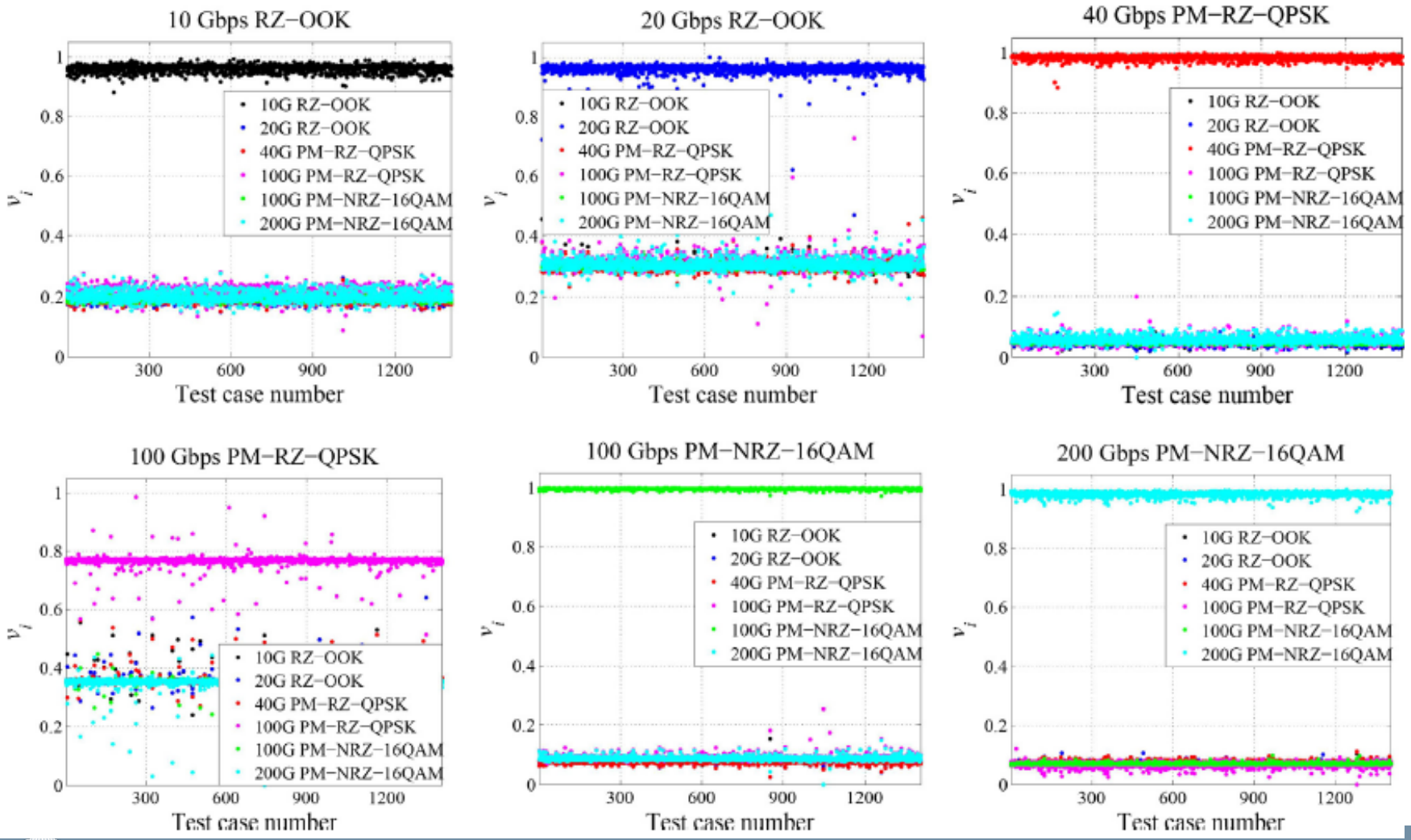




Modulation format recognition

Source 2

- MFR results: values of vector *v* for all MFs



Modulation format recognition

Source 2

- MFR results: confusion matrix
  - overall MFR accuracy 99.95%

A: 10 Gbps RZ-OOK
B: 20 Gbps RZ-OOK
C: 40 Gbps PM-RZ-QPSK
D: 100 Gbps PM-RZ-QPSK
E: 100 Gbps PM-NRZ-16QAM
F: 200 Gbps PM-NRZ-16QAM

		Predicted bit rate and MF					
		A	B	C	D	E	F
Actual bit rate and MF	A	100%	-	-	-	-	-
	B	-	99.93%	-	0.07%	-	-
	C	-	-	100%	-	-	-
	D	-	0.14%	0.08%	99.78%	-	-
	E	-	-	-	-	100%	-
	F	-	-	-	-	-	100%

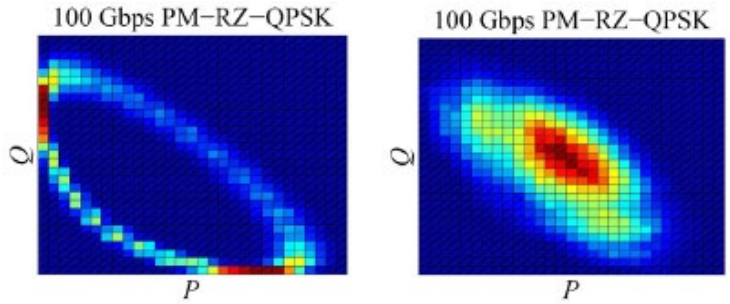
Modulation format recognition

Source 3

- Tan *et al.*, "Simultaneous Optical Performance Monitoring and Modulation Format/Bit-Rate Identification Using Principal Component Analysis", *Journal of Optical Communications and Networking*, vol. 6 n. 5, May 2014
- Paper objective: recognize modulation format and signal bit rate in optical fiber system
  - input
    - Asynchronous Delay-Tap Plots (ADTPs) of optical signal
  - output
    - Modulation Format
  - ML algorithm: PCA + minimum Euclidean distance

Modulation format recognition

Source 3

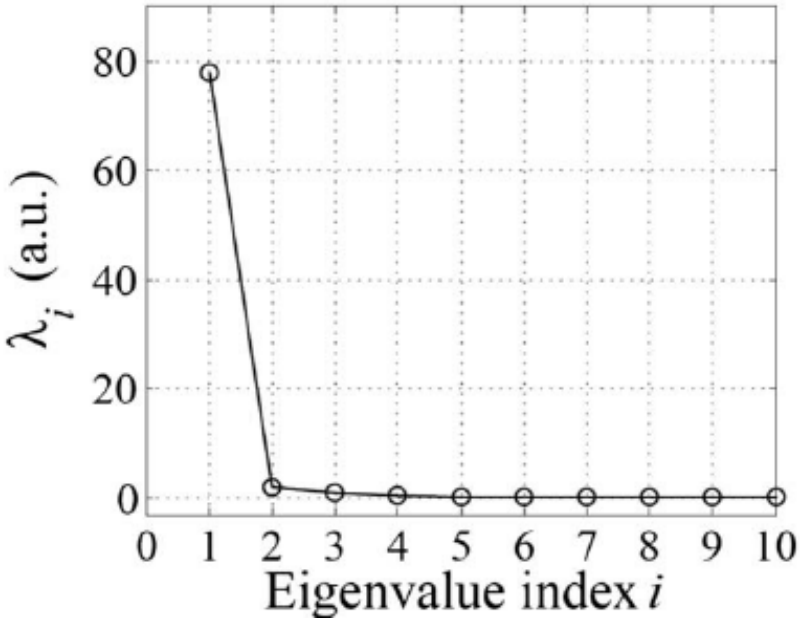


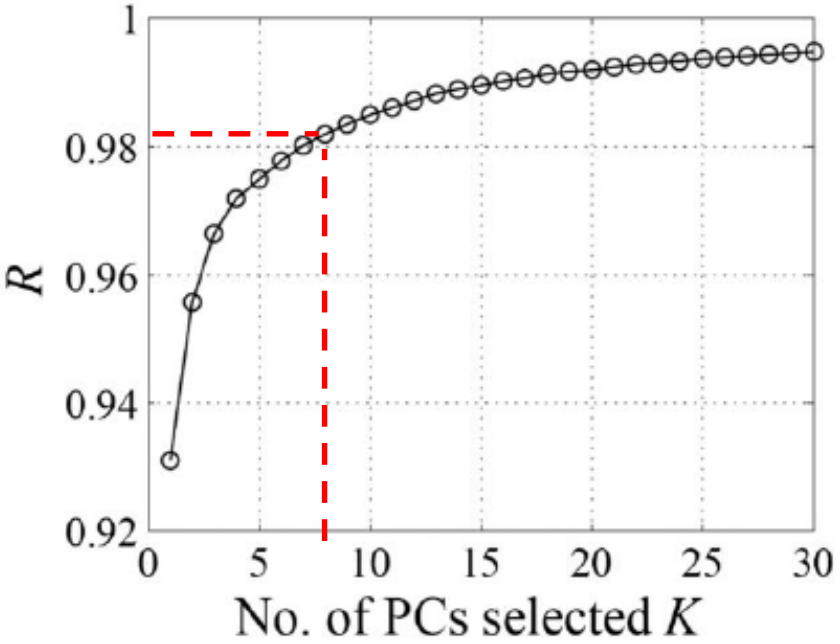
- ADTPs are treated as images with 30x30 bins (“pixels”)
  - Each “image” has 900 features
- PCA is used to reduce dimensionality from 900 to “K” principal components
- Dataset w/ 26208 ADTPs split into traing-test sets
  - 70%-30%; 60%-40%; 50%-50%
- After PCA, MFR is performed on a new sample by reducing its dimensionality and comparing its “new” features vector with the samples in the training set (minimum Euclidean distance)

Modulation format recognition

Source 3

- PCA: eigenvalues and “retained variance” w/ few PCs
  - 8 PCs are sufficent to have R>98%





Modulation format recognition

Source 3

- MFR results: confusion matrix
  - overall MFR accuracy w/ 2 PCs is 92.6%

A: 10 Gbps RZ-OOK
B: 20 Gbps RZ-OOK
C: 40 Gbps PM-RZ-QPSK
D: 100 Gbps PM-RZ-QPSK
E: 100 Gbps PM-NRZ-16QAM
F: 200 Gbps PM-NRZ-16QAM

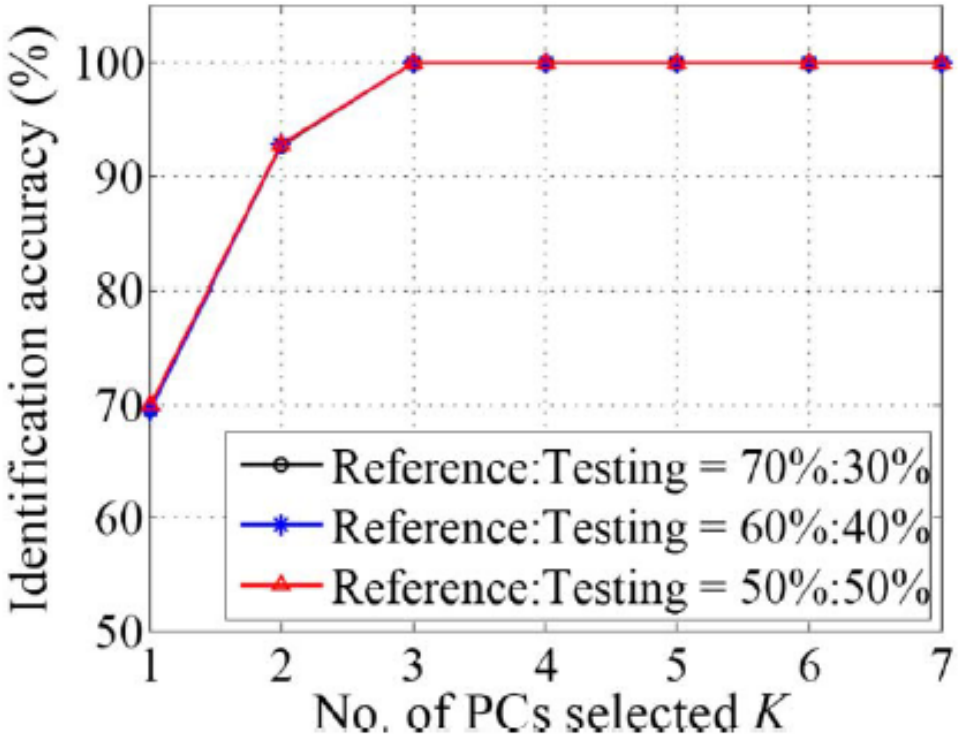
		Identified bit rate and MF					
		A	B	C	D	E	F
Actual bit rate and MF	A	98.05% **(100%)**	1.95%	-	-	-	-
	B	1.81%	98.19% **(100%)**	-	-	-	-
	C	-	-	98.45% **(100%)**	0.93%	-	0.62%
	D	-	-	1.51%	93.41% **(100%)**	3.79%	1.29%
	E	-	-	-	2.76%	83.28% **(100%)**	13.95%
	F	-	-	0.39%	0.94%	14.47%	84.2% **(100%)**

Accuracy is 100% w/ more than 2 components

Modulation format recognition

Source 3

- Accuracy vs training-test sets proportion and nr of PCs



Modulation format recognition

Source 4

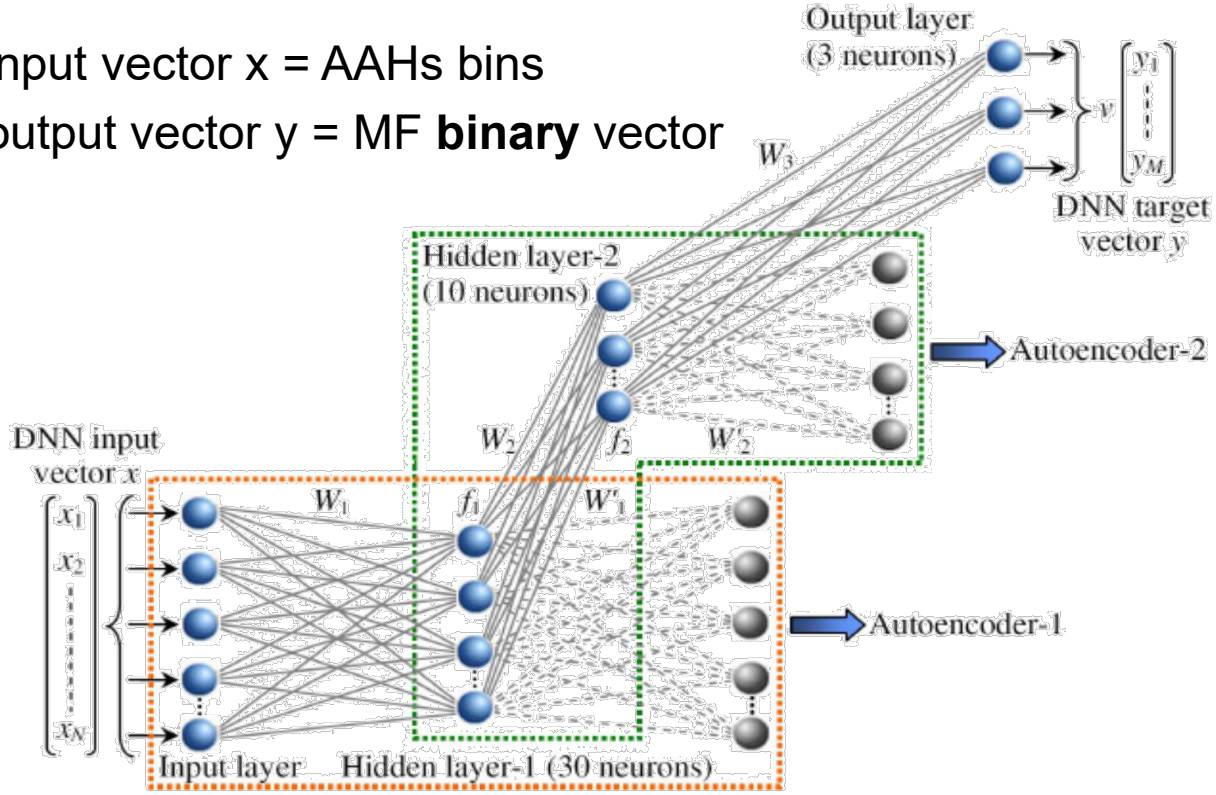
- Khan *et al.*, “Modulation Format Identification in Coherent Receivers Using Deep Machine Learning”, *Photonics Technology Letters*, vol. 28 n. 17, Sep. 2016
- Paper objective: recognize modulation format and signal bit rate in optical fiber system
  - input
    - Asynchronous Amplitude Histograms (AAHs) of optical signal
  - output
    - Modulation Format
  - ML algorithm: (Deep) Neural Network

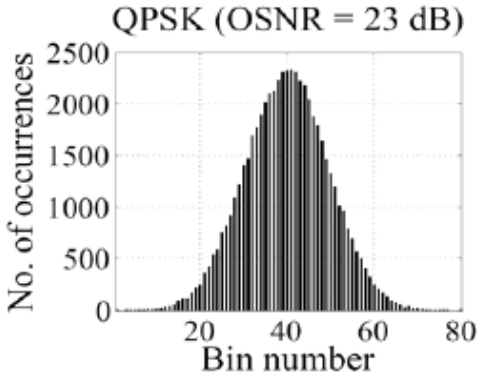
Modulation format recognition

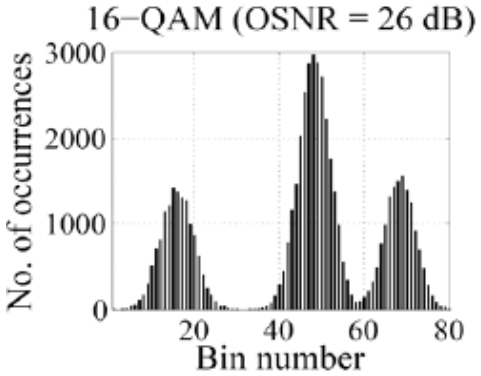
Source 4

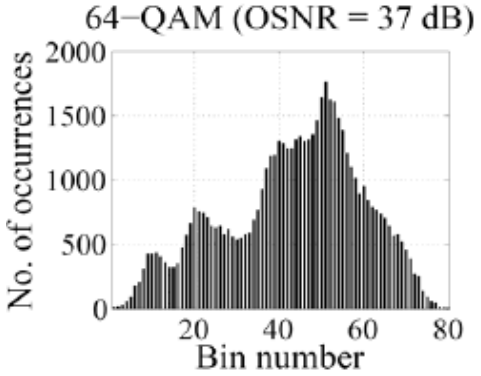
- Different MF and corresponding AAHs
- Deep NN with 2 hidden-layers
  - Each with an *autoencoder*

- input vector x = AAHs bins
- output vector y = MF **binary** vector





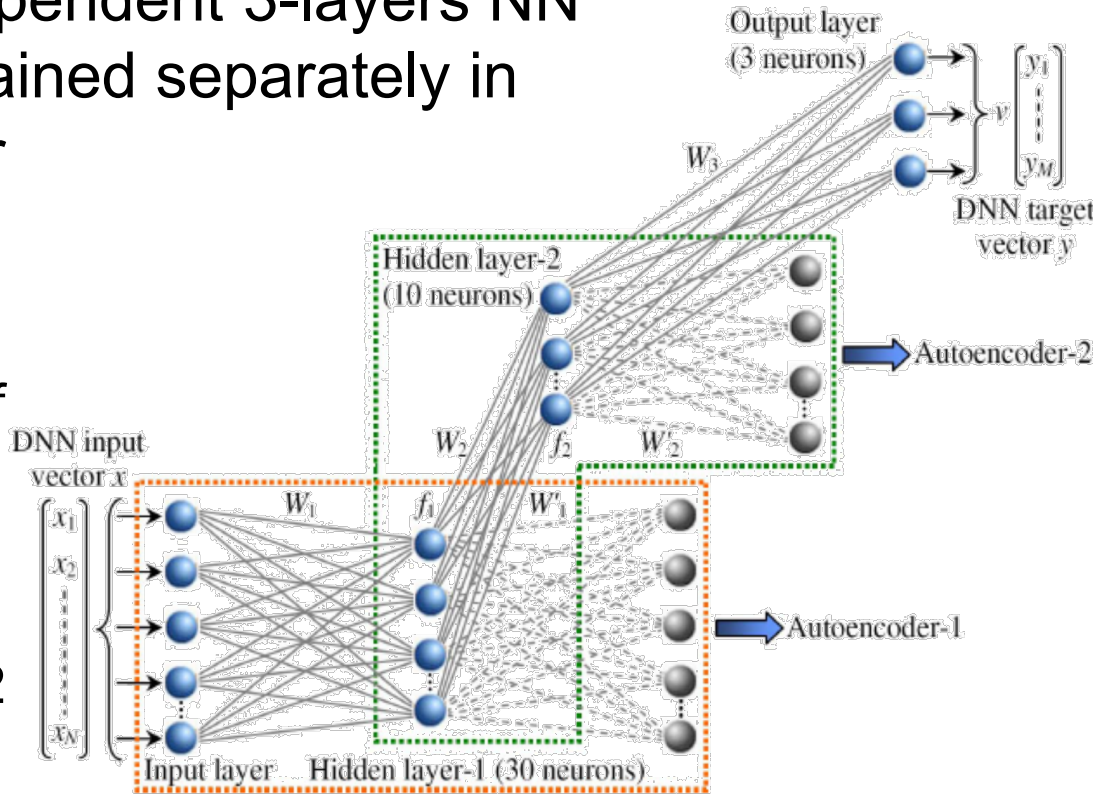




Modulation format recognition

Source 4

- Autoencoders are independent 3-layers NN (single hidden layer) trained separately in "unsupervised" manner
  - encoder (layers 1-2) + decoder (layers 2-3)
  - capture hidden features of the inputs (i.e., kind of dimens. reduction)
  - "labels" (y) of Autoenc.-1 correspond to DNN input
  - "labels" (y) of Autoenc.-2 correspond to the outputs of the 1st hidden layer
  - Final step ("fine-tuning"): train using "actual" outputs (i.e., y=MFs)



Dataset: 195 AAHs

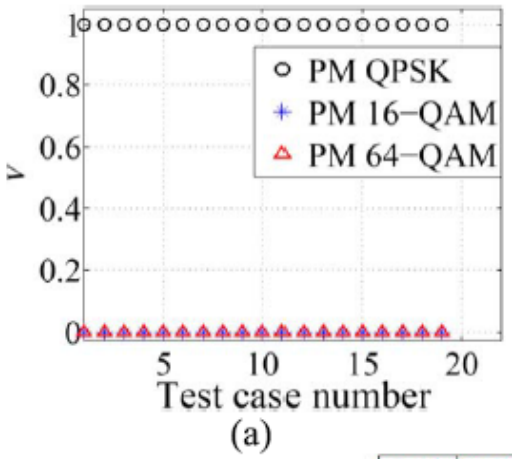
training : testing = 68% : 32%

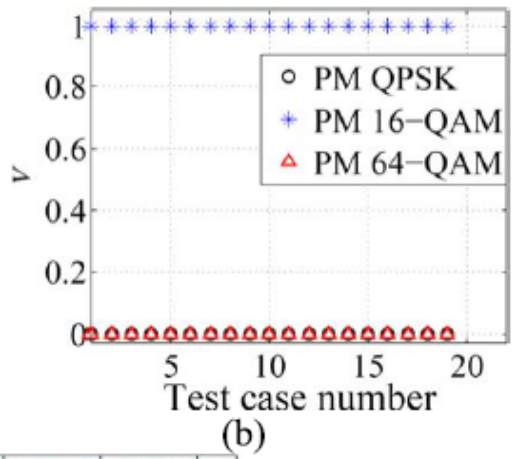
Modulation format recognition

Source 4

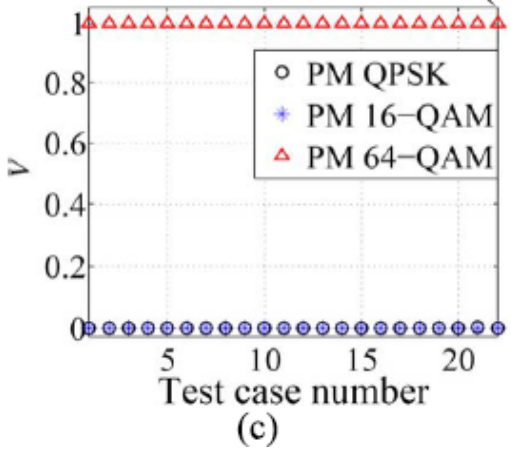
- MFR results: values of vector *v* for all MFs

PM QPSK





PM 16-QAM



PM 64-QAM

Modulation format recognition

Source 4

- MFR results: confusion matrix

		Identified Modulation Format		
		PM QPSK	PM 16-QAM	PM 64-QAM
Actual Modulation Format	PM QPSK	19 100%	0 0%	0 0%
	PM 16-QAM	0 0%	19 100%	0 0%
	PM 64-QAM	0 0%	0 0%	22 100%

- Effect of transmitted power on MFR accuracy