

## Declaration

I hereby declare that the work presented in this thesis titled *Automatic Modulation Classification using Deep Learning Techniques* submitted to Indian Institute of Technology Jodhpur in partial fulfillment of the requirements for the award of the degree of Doctor of Philosophy, is a bonafide record of the research work carried out under the supervision of Dr. Sandeep Kumar Yadav. The contents of this thesis in full or in parts, have not been submitted to, and will not be submitted by me to any other Institute or University in India or abroad for the award of any degree or diploma.



Yogesh Kumar  
P15EE202

## Certificate

This is to certify that the thesis titled *Automatic Modulation Classification using Deep Learning Techniques*, submitted by *Yogesh Kumar (P15EE202)* to Indian Institute of Technology Jodhpur for the award of the degree of *Doctor of Philosophy*, is a bonafide record of the research work done by him under my supervision. To the best of my knowledge, the contents of this report, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.



*Sandeep Kumar Yadav*  
*Ph.D. Thesis Supervisor*

## Acknowledgments

I thank my Ph.D. Thesis Supervisor, *Dr. Sandeep Kumar Yadav*, for introducing me to the area of signal processing and communication systems. Within the procedure, I found out many technical and non-technical elements of professional paintings. I am grateful to him for his *assist* and *endurance* as well as for constantly reminding me to be best within the little matters that I do every day.

I thank *Dr. Abhay Samant*, *Mr. Raghunandan* and *Mr. Varun* from National Instruments for introducing me to the hardware of wireless system which helped me to apprehend the ideas in a better way. I thank *Mr. Ashok Kumar*, *Mr. Gaurav Jajoo*, and *Mr. Manu Sheoran* for having fruitful technical discussions on numerous subjects at some stage in my stay at IITJ.

My stay at the Institute become a splendid experience because of my buddies, *Gaurav*, *Amit*, *Amrik*, *Gajendra*, *Mahmood*, *Surbhi*, *Manpreet*, and *Kanika*, for all the liveliness they infused into the non-academic part of the days at IIT Jodhpur...

Finally, I want to thank my spouse, *Anita* from the bottom of my heart for helping me to complete this adventure. She helped by watching our daughter *Navya* after I had to do work on my studies or to be on campus. She has been with me from the begin to the finish of my Ph.D. research and she will enjoy with me the culmination of this labor now that it's complete. I acknowledge and thank my *whole* circle of relatives, for the persistence and love which they ushered on me, and for bearing with me even when I was not spending much less time with them. I pay respects to my *mother and father* for all their *love, sacrifices and blessings*...

# List of Figures

Figures	Title	page
1.1	Military application of AMC	1
1.2	Link Adaptation	2
1.3	Opportunistic spectrum utilization	3
2.1	Spectral feature based classification strategy	12
3.1	Effect of carrier frequency offset on constellation	16
3.2	Graph of $R(f)$ for CFO of 60kHz	16
3.3	Symbol rate estimation	17
3.4	Proposed Modulation Classification Algorithm	17
3.5	Linear regression at 7dB SNR in (a) 4ASK and (b) 8PSK	18
3.6	Circle fitting at 7dB SNR in (a) 8PSK and (b) 8QAM	20
4.1	Block diagram of complete system.	24
4.2	SDP for sine wave at frequency of 100 Hz. (a) Effect of variation in $\mathcal{L}$ on SDP image for $\mathcal{G}=30$ . (b) Effect of variation in $\mathcal{G}$ on SDP image for $\mathcal{L}=15$ .	25
4.3	Formation of color image using ALPLT method.	26
4.4	SDP color images for all nine modulation schemes at 5dB and 15 dB SNR for particular $(\mathcal{L}, \mathcal{G})$ value.	27
4.5	Estimation of optimum value of $\mathcal{G}$ by maximizing natural and actual statistical difference between two classes.	28
4.6	Residual block structure.	29
4.7	DCNN model architecture. The first part of the Figure is the ResNet-50 [He et al., 2016] model used for the extraction of basic features. Each Conv_Block and Identity_Block has formed a bottleneck structure to reduce computational complexity. The second part is a fully connected network, which takes an array of 1000 outputs from the pre-defined ResNet-50 model to extract significant features.	31
4.8	Structure of (a) Conv_Block [He et al., 2016] (b) Identity_Block [He et al., 2016].	32
4.9	(a) Comparison of multiplications required in the bottleneck structure of Conv_Block and equivalent plain network. (b) Comparison of multiplications required in bottleneck structure of Identity_Block and equivalent plain network.	32
4.10	Inception ResNet V2 architecture [Szegedy et al., 2016].	34
4.11	Building blocks of Inception ResNet V2 [Szegedy et al., 2016] (a) Stem, (b) Reduction_A and (c) Reduction_B.	34
4.12	(a) General schema for Inception_ResNet blocks [Szegedy et al., 2016] and (b) Inception_A block [Szegedy et al., 2016].	35
4.13	Building blocks of Inception ResNet V2 [Szegedy et al., 2016] (a) Inception_ResNet_A, (b) Inception_ResNet_B, and (c) Inception_ResNet_C.	35
4.14	Hierarchy followed for modulation classification.	36
4.15	Accuracy versus SNR graph of 2ASK, 4ASK and 8ASK for ResNet-50 (Res) and Inception ResNet V2 (Inc) models.	38
4.16	Accuracy versus SNR graph of QPSK, 8PSK and 16QAM for ResNet-50 (Res) and Inception ResNet V2 (Inc) models.	38

4.17	Accuracy versus SNR graph of 2FSK, 4FSK and MSK for ResNet-50 (Res) and Inception ResNet V2 (Inc) models.	39
4.18	Average classification accuracy of QPSK and 16QAM.	39
4.19	Comparison of average classification accuracy of proposed methods with CNN1 and CNN2.	40
4.20	Comparison of average classification accuracy of proposed methods with CNN-AMC and traditional AMC methods.	41
5.1	A three-stage modulation classification procedure for eight modulation schemes with masking filters is shown. First stage : (a) Constellation of all modulation schemes are filtered through $F_1$ and classified into three groups. Second stage : (b) Constellation of 2ASK and 4ASK are filtered through $F_2$ and classified, (c) Constellation of QPSK and 8PSK are filtered through $F_3$ and classified, (d) Constellation of 8QAM, 16QAM, 32QAM and 64QAM are filtered through $F_4$ and classified into two groups. Third stage : (e) Constellation of 8QAM and 16QAM are filtered through $F_5$ and classified, (f) Constellation of 32QAM and 64QAM are filtered through $F_6$ and classified. (g) Description of the working procedure of all five filters. Functional architecture of (h) ResNet-50 Residual Block, and (i) Inception Residual Block.	44
5.2	Accuracy of developed method with (a) ResNet-50 and (b) Inception ResNet V2 for eight modulation schemes. (c) Proposed method comparison with GP-KNN in AWGN, ML classifier with parameter estimated by SQUAREM-PC in GMM (N=2) and one sample 2D K-S classifier with parameter estimated by ECM in GMM (N=2) for 2ASK, QPSK, 8PSK, and 16QAM modulation schemes. (d) Comparison of average classification accuracy with and without masking filters for ResNet50 and Inception ResNet V2.	46
6.1	DCNN architecture.	51
6.2	Generation of 2D-FFT from DM of I-Q diagram.	52
6.3	2D-FFT dataset generated from DM of (a) BPSK, (b) QPSK, (c) 8PSK, (d) 16QAM, and (e) 64QAM.	52
6.4	(a) Accuracy of the developed method with SNR for all five modulation schemes. (b) Performance comparison of the model with signal length. (c) Classification performance of the model with phase offset. BPSK, QPSK, and 8PSK modulation schemes are tested at 5 dB SNR and 16QAM, and 64QAM are tested at 20 dB SNR.	54
6.5	Confusion matrix of proposed DCNN model for all five classes. Each class is tested with 1000 signal realization for a range of SNR (0, 16) dB.	55
6.6	Comparison of proposed method with naive-based and SVM classifiers.	55
7.1	System model	57
7.2	Modulation classification approach.	59
7.3	Parallel processing of algorithm for four ranges of symbol rate.	62
7.4	FPGA implementation of modulation classification approach.	63
7.5	Optimization of $\alpha$ (Graph shows maximum accuracy at $\alpha=0.5$ ).	65
7.6	Accuracy versus SNR for 5k-10k symbol rate range and $f_s=10M$ .	65
7.7	Accuracy versus SNR for 10k-15k symbol rate range and $f_s=15M$ .	66
7.8	Accuracy versus SNR for 15k-20k symbol rate range and $f_s=30M$ .	66
7.9	Accuracy versus SNR for 20k-25k symbol rate range and $f_s=40M$ .	67
7.10	Accuracy versus CFO for 5k-10k symbol rate range and $f_s=10M$ .	67
7.11	Accuracy versus CFO for 10k-15k symbol rate range and $f_s=15M$ .	68
7.12	Accuracy versus CFO for 15k-20k symbol rate range and $f_s=30M$ .	68
7.13	Accuracy versus CFO for 20k-25k symbol rate range and $f_s=40M$ .	69

## List of Tables

<i>Figures</i>	<i>Title</i>	<i>page</i>
3.1	Confusion matrix for ASK (7dB)	20
3.2	Confusion matrix for PSK (7dB)	20
3.3	Confusion matrix for QAM (7dB)	21
4.1	Candidate modulation schemes considered for classification.	25
4.2	Dataset and system parameters used for DCNN training	37
4.3	Comparison of results with existing methods	40
4.4	Comparison of results with GP-KNN	41
5.1	Filters specifications	48
6.1	Comparison between different classifiers given in [Wong <i>et al.</i> , 2008] and proposed work for $\Theta_3$ modulation set	56

## List of Symbols

Symbol	Description
$\Delta p$	Oversampling factor resolution
$\gamma_{max}$	Maximum value of the spectral power density of the normalized and centered instantaneous amplitude
$\sigma_{ap}$	Standard deviation of the absolute value of the non-linear component of the instantaneous phase
$\sigma_{dp}$	Standard deviation of the non-linear component of the direct instantaneous phase
$\mathbb{S}$	Evaluation of the spectrum symmetry around the carrier frequency
$\sigma_{aa}$	Standard deviation of the absolute value of the normalized and centered instantaneous amplitude of the signal samples
$\sigma_{af}$	Instantaneous frequency
$\sigma_a$	Instantaneous amplitude
$\mu_{42}^a$	Kurtosis of the normalized and centered instantaneous amplitude
$r$	Received complex baseband signal
$\mu_{42}^f$	Kurtosis of the normalized and centered instantaneous frequency
$R_r^{\alpha}(\tau)$	Cyclic autocorrelation
$S_r(f)$	Spectral correlation function
$s$	Transmitted complex baseband signal
$\eta$	Probability density function of AWGN
$\rho$	Correlation coefficient
$\Delta\phi$	Phase offset
$\hat{\alpha}$	Fading channel attenuation
$\mathcal{L}$	Likelihood function
$N$	Number of symbols
$\Delta f$	Carrier frequency offset
$p < . >$	Pulse shaping filter
$\mathfrak{M}$	Modulation set
$f'_c$	Estimated carrier frequency
$f_s$	Sampling frequency
$OS$	Oversampling factor
$r_R$	Passband received signal
$f_c$	Carrier frequency
$f'$	Estimated frequency
$R_s$	Symbol rate
$\mathcal{L}$	Sample delay in SDP formation
$\mathcal{G}$	Amplification factor in SDP formation
$d(i, j)$	Density of points in $(i, j)^{th}$ grid section
$I(i, j)$	Intensity of $(i, j)^{th}$ pixel
$\mathcal{F}$	Fast Fourier Transform
$\varepsilon$	Constellation error
$I_i$	Ideal constellation points
$M$	Modulation order
$\Delta T$	Symbol time offset

## List of Abbreviations

<i>Abbreviation</i>	<i>Full form</i>
2D-FFT	Two-Dimensional Fast Fourier Transform
ALPLT	Adaptive Local Power Law Transform
ALRT	Average Likelihood Ratio Test
AMC	Automatic Modulation Classification
ANN	Artificial Neural networks
ASK	Amplitude Shift Keying
AWGN	Additive White Gaussian Noise
CDM	Constellation Density Matrix
CF	Carrier Frequency
CFO	Carrier Frequency Offset
CNN	Convolution Neural Network
CR	Cognitive Radio
CSI	Channel State Information
CSV	Comma Separated Values
DCNN	Deep Convolution Neural Network
DFT	Discrete Fourier Transform
DL	Deep Learning
FB	Feature Based
FFT	Fast Fourier Transform
FIFO	First In First Out
FPGA	Field-Programmable Gate Array
FSK	Frequency Shift Keying
GLRT	Generalized Likelihood Ratio Test
GMM	Gaussian Mixture Model
GP-KNN	Genetic Programming- k Nearest Neighbour
GPU	Graphics Processing Unit
HLRT	Hybrid Likelihood Ratio Test
HOC	Higher Order Cumulants
IID	Independent and Identically Distributed
K-S	Kolmogorov-Smirnov
LB	Likelihood Based
LO	Local Oscillator
MFCC	Mel-frequency Cepstral Coefficients
ML	Machine Learning
MSE	Mean Square Error
MSK	Minimum Shift Keying
NI	National Instrument
NLP	Natural Language Processing
OP	Optimum Parameters
OS	Over Sampling
PDF	Probability Density Function
PO	Phase Offset
PSK	Phase Shift Keying
PU	Primary User
QAM	Quadrature Amplitude Modulation
ReLU	Rectified Linear Unit
RF	Radio Frequency
RRC	Root Raised Cosine
SCF	Spectral Correlation Function
SD	Standard Deviation



<i>Abbreviation</i>	<i>Full form</i>
SDP	Symmetric Dot Pattern
SDR	Software Defined Radio
SNR	Signal to Noise Ratio
SR	Symbol Rate
STO	Symbol Time Offset
SU	Secondary User
SVM	Support Vector Machine
VHDL	Very High Speed Integrated Circuit Hardware Description Language
VI	Virtual Instrument