Graph Deep Learning Models for Automated Modulation Classification in Cognitive Radio Systems

Final Thesis Report

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By

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May 2022

10th May 2022

Format of 'Certificate from the Supervisor'

CERTIFICATE

This is to certify that the thesis entitled "Graph Deep Learning Models for Automated Modulation Classification in Cognitive Radio Systems" submitted by Sanghita Chakraborty, ID No 2018A8TS0876H, in partial fulfillment of the requirement of BITS F421T Thesis embodies the original work done by him under my supervision.

Signature of the Supervisor Signature of the Co-supervisor **Name & Designation Name & Designation** Date: 17-03-2022 Date: 17-03-2022

Thesis Title: Graph Deep Learning Models for Automated Modulation Classification in Cognitive Radio Systems

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Semester: Eighth Semester

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Abstract:

In Electronics and Telecommunication, Modulation is considered as a methodology used to vary one or more than one feature of a periodic waveform (called carrier signal) using another signal known as the modulation signal which contains information to be transmitted. AMC or the Automatic Modulation Categorization is a method to predict the modulation type of an unknown Radio Signal whose signal parameters are not known to us. Various researchers have worked on different ways to perform AMC. Our idea is to come up with Deep Learning algorithms based on Graph Convolutional Network on a weighted visibility graph representation of time series of various modulated signals.

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Introduction:

AMC or Automatic modulation categorization is a method to predict the category of modulation of a given radio signal with unknown signal parameters. This method is used in various fields such as spectrum sensing and monitoring, adaptive modulation switching, threat analysis, electronic warfare, etc. In the last two decades, many researchers around the world have proposed various ML/DL-based methods for AMC using radio signals. We have introduced a new idea of using visibility graph to represent the time series for various modulated signals and try to measure the different edge strengths for different graphs. In the next portion, we will be covering certain important definitions related to our work.

Modulation Types:

Modulation is defined as the method for varying characteristics of a carrier wave in accordance to a modulating signal. Modulation helps in transmitting a signal over bandpass frequency range.This section will define various modulation signals that will be considered.

- BPSK: Binary Phase Shifting Key is a two-phase modulation methodology. The 0s and the 1s in a binary message are shown by two different phase states in the carrier signal.It is a form of M-PSK modulation that employs M unique symbols to represent the input data. BPSK has two-phase reversals (0 and 180 degrees)

- QPSK: In Quadrature Phase Shift Keying, two information bits are modulated at once, hence one of the four-phase shift states in the carrier signal (0,90,180 and 270 degrees).

- 64-QAM: QAM is a modulation method in which two carrier signals having the same frequency and phase shift of 90 degrees are used. 64-QAM outputs 64 possible signal combinations, each symbol constituting six bits.

- PAM4: Pulse Amplitude Modulation is a method where the amplitude of the carrier signal is changed. PAM4 has 4 amplitude levels for the digital signal modulation.

- FSK: Frequency Shift Keying is modulation method in which the frequency of the carrier wave is changed based on information signal. CPSK stands for Continuous phase frequency shift keying - a type of FSK in which phase of modulated signal is made continuous. GFSK stands for gaussian frequency shift keying. It utilizes gaussian filters to smoothen the transitions occurring due to frequency shift.

- B-FM: Broadcast-frequency modulation - a method used for analog modulation. The frequency of the carrier signal is varied based on data signal. It is used a lot in FM radio signal broadcast.

- SSB-AM/DSB-AM: Amplitude modulation is another method for ananlog modulation.The concept is to vary the amplitude of carrier signal based on information signal. The common amplitude modulation is also called Dual Side Band AM (DSB-AM).In order to get single side-band AM (SSB-AM), bandpass filters are used to consider signal only from one side-band

Time Series :

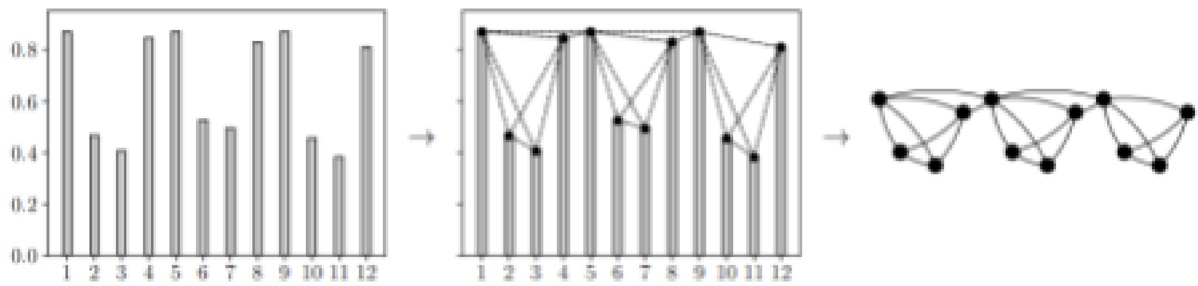
A time series is defined as a series of data points that are listed in chronological order.They are usually sampled in regular equi-distant points in time. These are an extremely simplistic representation however they can be utilized to capture very complex systems. This form of data can be transformed into graphs with the help of abstract mapping. This makes it easy to relate Time series analysis to graph theory.

Graphs:

A Graph is a mathematical structure represented by a set of objects, some of which are connected representing some form of relationship between the objects connected. Formally (Mathematically) it is represented as a set G = (V, E), where V is the set of vertices (or nodes) representing the objects, and E is the set of edges (or links) representing the relations among pairs of objects.

Visibility Graphs:

The visibility graph of a time series T is the graph with n nodes that represents all the n observations sampled in T with the condition that an edge between two nodes will exists if and only if there is no obstacle while we draw a line from the top of the bar corresponding to one observation to that of another in a bar plot of T. The below figure will be helpful in understanding this further.



Mathematically, it can be formulated as follows. The edge between two nodes can be there only if it satisfies the mathematical condition below.

$$x(tc) < x(ta) + (x(tb) - x(ta)) * (tc - ta)/(tb - ta) , a < c < b$$

where, x(ta) and x(tb) are data points at arbitrary time events ta and tb and tc is another time event between ta and tb.

The visibility graphs can be weighted as well. In a weighted graph, each of its edges has a numerical weight a numerical weight which indicates some relevant information such as cost, distance, etc. The edge weight of visibility graph can be calculated as:

$$w_{ab} = \arctan \frac{x(t_b) - x(t_a)}{t_b - t_a},$$

Signal Generation:

This work has considered 9 different modulation types described in details in “Modulation Types” section. These contain both analog and digital modulation radio signals. Six tof them are digitally modulated radio signals which includes BPSK, QPSK, M-array quadrature amplitude modulation (64-QAM), pulse amplitude modulation (PAM4), GFSK and CPFSK modulation types. Rest of the three are analog modulated radio signals that includes B-FM and amplitude modulation (DSB-AM and SSB-AM).

The sampling frequency used in this work for the radio signal is 200KHz. Each radio signal frame consists of 1024 samples.

The signal generation has been done according to the method used in [1].

Results (Part 1 -Mid Semester):

The main objective so far was to generate the visibility graphs for various modulation types. While creating each of the graphs, we have considered 1000 frames of each modulation types. Each frame containing 1024 samples. We have created separate weighted visibility graphs for Inphase, Quadrature, Magnitude, and Phase components of the signals. We have used ts2vg and networkx libraries for constructing the graphs. The entire data points have been represented in the form of bins (20 bins). Hence the graph contains 21 nodes.
Following are the weighted visibility graph representation for various components of BPSK modulated signals.

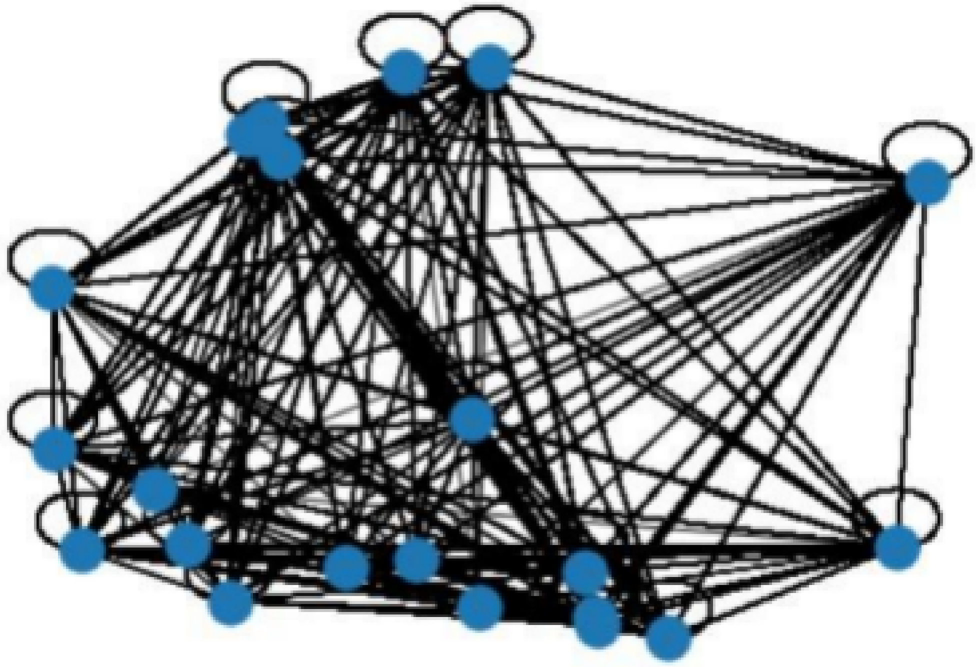


Fig: Weighted visibility graph for inphase (real component) of BPSK modulated signals

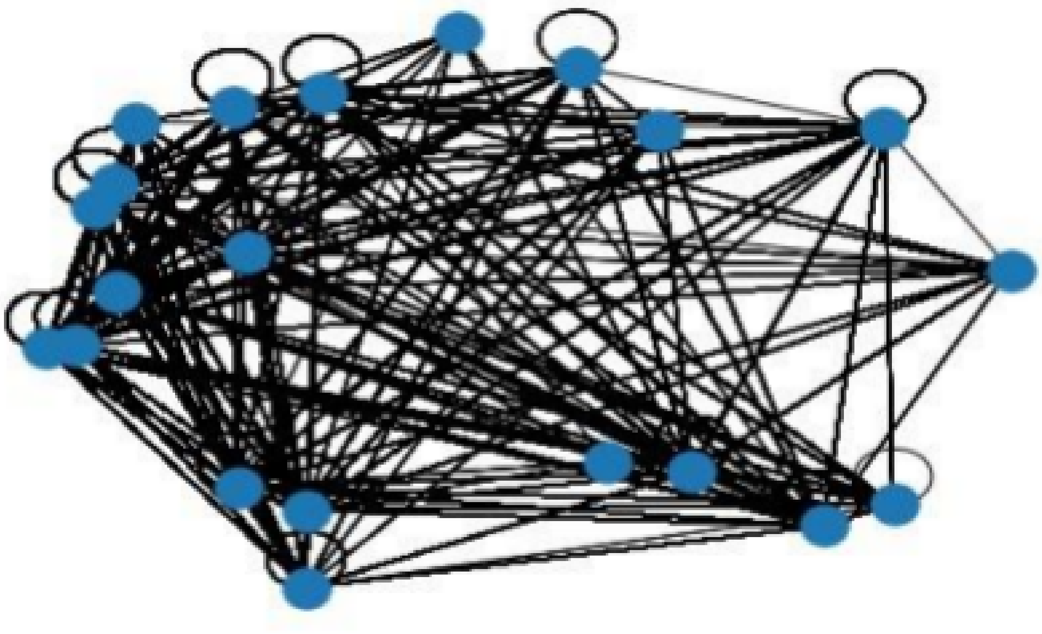


Fig: Weighted visibility graph for Quadrature(imaginary component) of BPSK modulated signals

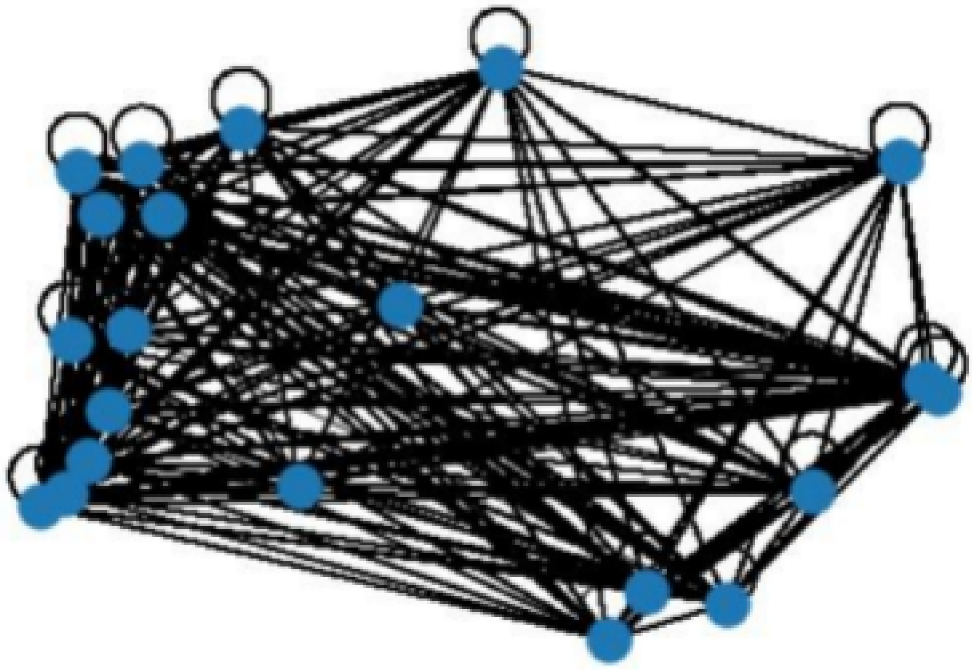


Fig: Weighted visibility graph for Magnitude component of BPSK modulated signals

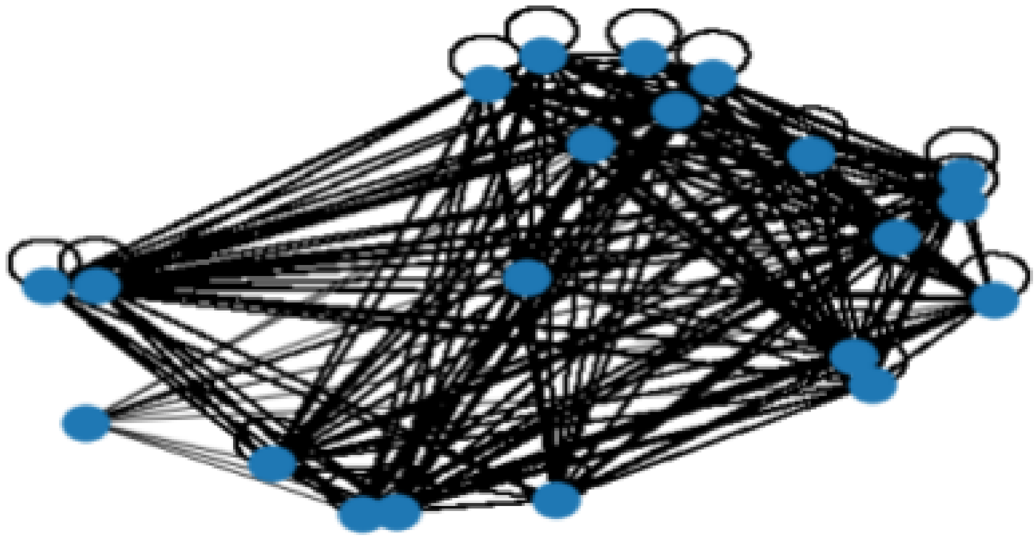


Fig: Weighted visibility graph for Phase component of BPSK modulated signals

PART-2 (Post Midsem)

Graph Classification:

Approach 1 (GCN)

The first method we have tried is using Graph Convolution Network. We have used the StellarGraph library for this. The graph classification module consists of layers as shown in the figure below. The input is the graph which is represented by its adjacency and node features matrices

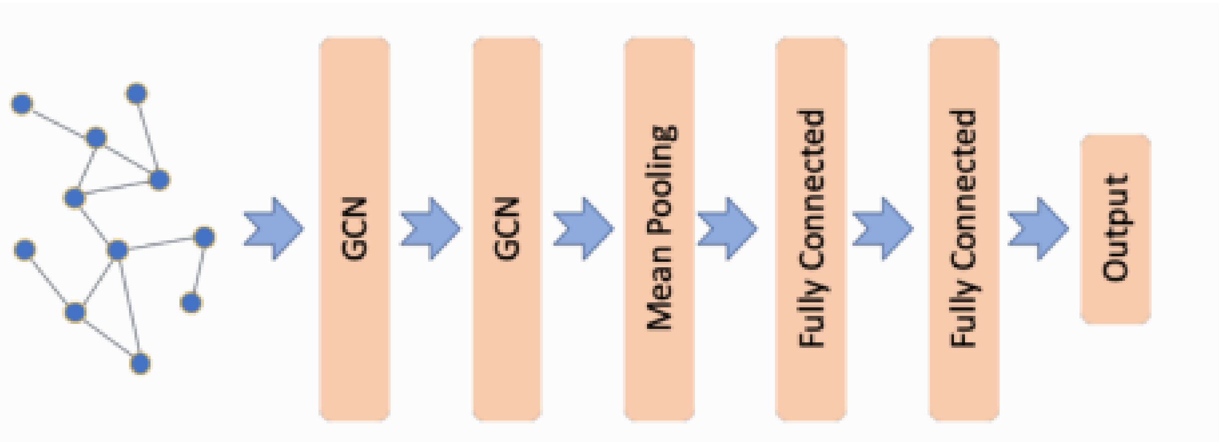
GCNs are extremely useful neural network architecture to perform machine learning on graphs

For graph convolutional network, we are given a graph set G = (V,E) and the GCN takes as input the following things:

- an input feature matrix of size $N \times F$(say ***X*),** where N is the number of nodes and F is the number of input features for each node, and
- an $N \times N$ matrix which is basically the adjacency matrix of the graph For the

classification purpose, we have used StellarGraph's GraphClassification module.

The first two layers are Graph Convolutional where each layer is having 64 units and relu activations. The subsequent layer is a mean pooling layer followed by two fully connected layers with 32 and 16 units and relu activations. The final layer represents the output layer with as many number of units as the number of classes and sigmoid activation.



Approach 2 (Image Classification)

In this approach, our aim was to use the visibility graph images for various time series and using CNN and transfer learning, perform image classification.

Transfer Learning:

Transfer learning is a method widely used in machine learning, where we reuse a pre trained model for the model on a present task.

A pre-trained model is essentially a saved neural network which has already been trained on a very large dataset (for image classification purposes, it's trained on large scale image classification task) We can use the same model as it is for our new work or customize it according to your purpose.

The concept of transfer learning is that if a model is trained on a large and general enough dataset, this model can be used as a generic modelfor all type of image classification problems.

Convolutional Neural Network:

A Convolutional Neural Network (ConvNet/CNN) is a Deep Learning algorithm where we provide an image as input, and the model assigns learnable weights and biases to various aspects in the image and accordingly classify the image. As compared to other classification algorithms CNN requires much lesser pre-processing

Approach 3 (Using Feature Extraction)

In this approach our target was to extract various graph properties such as clustering coefficient etc and use classification models such as SVM on that. This method is called feature based supervised graph machine learning

The features that we used are :
<u>Degree Centrality</u>: It is the most common centrality metrics metric. It measures the number of edges being incident

<u>Clustering Coefficient</u>: The clustering coefficient measures howthe nodes in a graph are

clustered together. Mathematically, It is the fraction of triangles (complete subgraph of three nodes and three edges) around a node and is equal to the fraction of the node's neighbors that are neighbors of each other.

Global Efficency: It is the average of the inverse shortest path length for all pairs of nodes.

SVM (Support Vector Machine) :

Support Vector Machine or SVM is one of the most frequently used Supervised Learning algorithms, used for Classification or Regression problems (mostly classification)

SVM algorithm creates the best fit decision boundary that can separate n-dimensional space into classes so that new data point is correctly classified in future. This best decision boundary is known as the hyperplane

Results (Final):

- On application of GCN on the dataset containing visibility graphs of all the 9000 time series, We achieved an accuracy of 51.2% approximately.

- On plotting the graph images of various time series in circular plot format using networkx library, we found that there weren't any specific difference between the graphs plotted for various classes. Hence we finally ruled out the transfer learning based methodology.

- In the third approach of feature based supervised learning, our model could only provide an accuracy of around 49%

Based on our analysis of the three approaches, it is evident that the visibility graph is not able to capture the essence of the modulated signals totally. In order to capsulate the phase difference information and other properties of the modulated signals, there has to be a more sophisticated signal processing data. We are going to work with the team responsible for giving the datatable for all the processed signals to resolve this issue so that we can test all our methodologies on the new data.

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