APPENDIX 1

TITLE OF PROJECT REPORT

5G NR Test Models using MATLAB 5G Toolbox

AN INTERNSHIP REPORT

5G NR Test Models using MATLAB 5G Toolbox

Submitted by

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MONTH & YEAR

APRIL 2025

BONAFIDE CERTIFICATE

Certified that this project titled **"5G NR Test Models using MATLAB 5G Toolbox "** is the bonafide work of **JOTHI SORUBAN M, PARTHASARATHY VT** who carried out the project work under my supervision.

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INTERNAL EXAMINER **EXTERNAL EXAMINER**

ACKNOWLEDGEMENT

We are personally indebted to a few people who gave us their useful insights to aid in our overall progress for this project. A complete acknowledgement would therefore be encyclopedic. First, we would like to give our deepest gratitude to our parents for permitting us to take up this course.

We record our sincere thanks to **Dr. V. SUMATHY** Principal for her encouraging us to do this project.

We express our sincere thanks to Mr. LINGESHWARAN.M, M.E**.,** Ph.D., Head of the Department, Electronics and Communication Engineering, for her encouragement in caring out this project.

We express our profound and sincere thanks to our Project Coordinator, Mr. LINGESHWARAN.M, M.E**.,** Ph.D. Assistant Professor Electronics and Communication Engineering for her enlightening thoughts and remarkable guidance that helped us in the successful completion of our project.

We express our deep sense of thanks and gratitude to our Supervisor Mr. NARASIMAN.D, BE, supervisor**,** Trainer, DADB OF India, for her support and valuable guidance to complete our project successfully.

We also express our sincere thanks to our department faculties for their encouragement to do this project.

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ABSTRACT

This project focuses on the development and evaluation of 5G New Radio (NR) test models, specifically Test Model 1.1 (TM1.1) and Test Model 3.1 (TM3.1), using the MATLAB 5G Toolbox. These models are designed to validate the performance of 5G NR transmitters under various modulation schemes, including QPSK, 16-QAM, and 64-QAM. By generating standard-compliant waveforms based on 3GPP TS 38.141 specifications, the project assesses signal fidelity, spectral characteristics, and modulation accuracy. A comparative analysis is conducted to identify deviations in signal quality indicators such as EVM (Error Vector Magnitude) and ACLR (Adjacent Channel Leakage Ratio) across different test conditions. The results support the verification of transmitter compliance with 3GPP standards and provide insights into the impact of modulation formats on system performance.

LIST OF FIGURES

LIST OF ABBREVIATIONS

5G NR	5G New Radio
TM 1.1	Test Model 1.1
FR1	Frequency Range 1
FR2	Frequency Range 2
FDD	Frequency Division Duplex
TDD	Time Division Duplex
QPSK	Quadrature Phase Shift Keying
QAM	Quadrature amplitude modulation
EVM	Error Vector Magnitude
ACLR	Adjacent Channel Leakage Ratio
AWGN	Additive white Gaussian noise
PSD	power spectral density
CCDF	Complementary cumulative distribution function

INTRODUCTION

1.1Overview

With the evolution of mobile networks to 5G, ensuring signal quality and compliance with 3GPP standards is essential. This project explores the development of 5G NR (New Radio) test models using MATLAB’s 5G Toolbox. Specifically, Test Models TM1.1, TM3.1, etc... are implemented to validate transmitter performance. These models emulate realistic signal conditions and are used for performance and compliance validation of 5G NR systems

1.2Objectives

- **Develop 5G NR Test Models:**
  Implement 3GPP-defined test models such as TM1.1 using MATLAB 5G Toolbox to emulate standard-compliant 5G NR downlink waveforms.
- **Validate Transmitter Performance:**
  Generate test signals and analyze key performance metrics such as EVM (Error Vector Magnitude), ACLR (Adjacent Channel Leakage Ratio), and spectral flatness.
- **Assess 3GPP Standard Compliance:**
  Evaluate the generated waveforms against 3GPP TS 38.141 requirements to ensure compliance in terms of signal characteristics and spectral constraints.
- **Compare Modulation Schemes:**
  Investigate the effect of different modulation schemes (QPSK, 16-QAM, 64-QAM, etc.) on signal performance using the developed test models.
- **Identify Signal Deviations:**
  Detect and analyze deviations from expected performance under varying transmission conditions and modulation formats.
- **Support Transmitter Testing and Optimization:**
  Provide a framework for testing, validating, and optimizing transmitter design in accordance with 5G NR standards.

2. NR TEST MODEL WAVEFORM CONFIGURATION PANNEL:

- **Frequency Range: FR1 (410 MHz – 7.125 GHz)**

  This specifies the operating frequency band. **FR1-** sub-6 GHz

- **Test Model: NR-FR1-TM1.1**

  This defines the specific 5G NR test model being used. **TM1.1** is a standard 3GPP-defined waveform designed for single-antenna

- **Subcarrier Spacing (kHz): (15, 30, 60)**

  This sets the spacing between adjacent subcarriers in the OFDM modulation scheme.

Overlapping spectra of OFDM techniques:

Orthogonal Frequency Division Multiplexing (OFDM) is a widely used modulation technique in modern wireless communication systems due to its high spectral efficiency and robustness against multipath fading. One key characteristic of OFDM is its overlapping subcarrier spectra

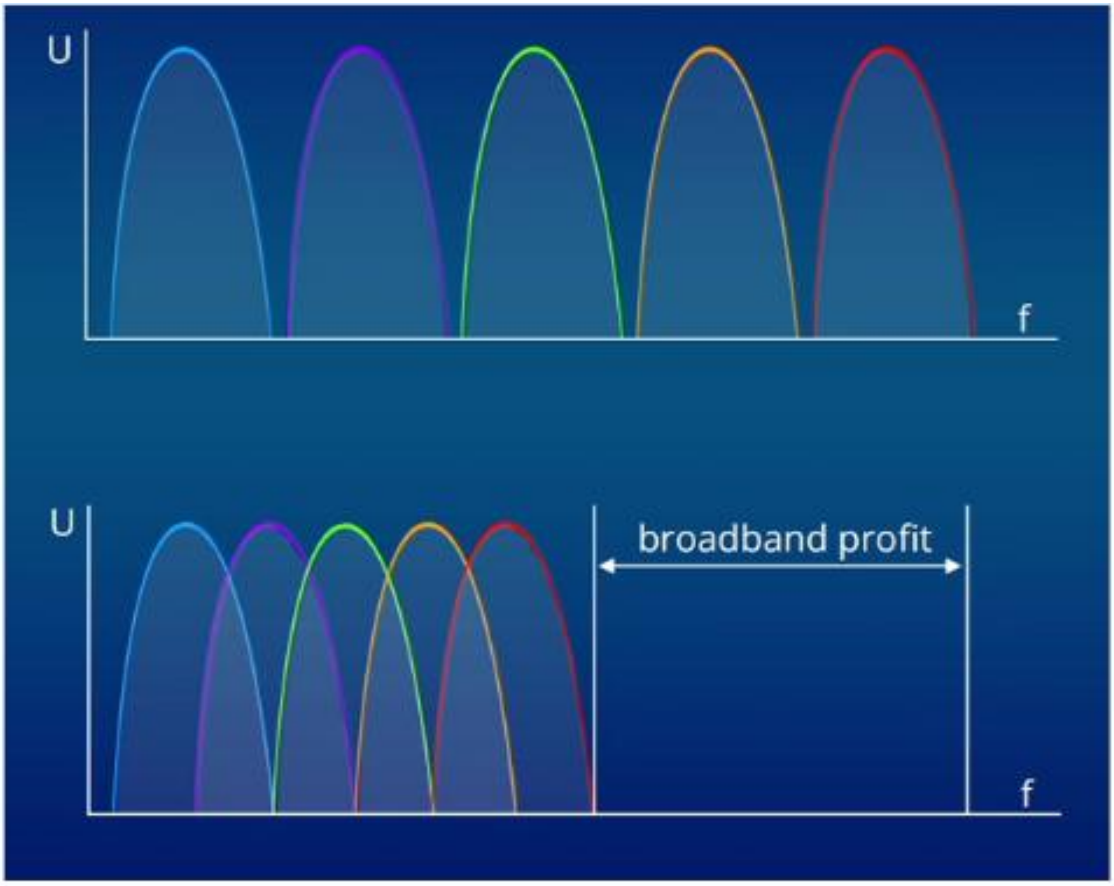

Fig 1.1 – Overlapping spectra of OFDM technique

2.1 SUB CARRIER SPACING

Subcarrier spacing refers to the frequency separation between adjacent subcarriers in an Orthogonal Frequency Division Multiplexing (OFDM) system. It plays a crucial role in determining the system performance, latency, and resistance to channel impairments. In OFDM, subcarriers are spaced such that they remain orthogonal to each other, allowing their spectra to overlap without causing inter-carrier interference. The spacing is inversely related to the OFDM symbol duration — wider spacing leads to shorter symbol times and lower latency, while narrower spacing offers better resilience to frequency-selective fading.

In 5G NR (New Radio), subcarrier spacing is scalable and defined as Δf=15×2n\Delta f = 15 \times 2^nΔf=15×2n kHz, where n=0,1,2,3,4n = 0, 1, 2, 3, 4n=0,1,2,3,4, resulting in spacings of 15, 30, 60, 120, and 240 kHz. This flexibility allows 5G to support diverse use cases, from enhanced mobile broadband to ultra-reliable low-latency communications, by adapting to varying bandwidth and deployment scenarios.

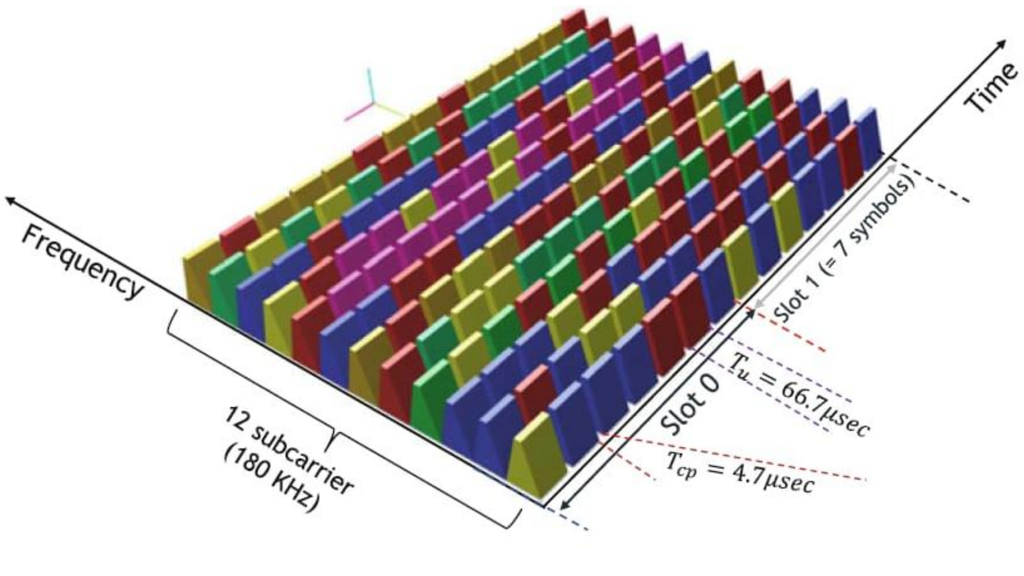

Fig 2.1 – Subcarrier spacing

- **Channel Bandwidth (MHz): 20**

  A **20 MHz** channel provides enough frequency space for testing moderate-to-high data rates while keeping system complexity manageable during validation.

- **Duplex Mode: TDD (Time Division Duplex), FDD (Frequency Division Duplex)**

  TDD allows uplink and downlink transmissions to occur at different times but on the same frequency. E.g. – wakki Takki

  FDD allows uplink and downlink transmissions in different spectrum in between guard band also using in this spectrum E.g. – Mobile communication spectrum.

- **Subframes: 20**

  This sets the duration of the generated waveform in units of subframes (1 subframe = 1 ms). **20 subframes** equate to a 20 ms waveform, offering enough data to observe and analyse temporal behaviour and signal stability.

- **Cell Identity: 1**

  This is a unique identifier for the simulated cell. The **Cell ID** is used in the physical layer for scrambling.

- **Windowing Source: Custom**

  Specifies how windowing (signal smoothing) is applied. **Custom** allows the user to manually define how the transition between OFDM symbols is handled, which can help reduce out-of-band emissions.

- **Windowing (%): 0**

  A value of **0%** means no additional windowing is applied, potentially increasing spectral leakage but simplifying the waveform.

- **Sample Rate Source: Auto**

  This automatically selects the sampling rate based on other parameters (e.g., bandwidth, subcarrier spacing

- **Phase Comp.: (Unchecked)**

  This checkbox enables or disables **phase compensation**. Leaving it unchecked means phase correction is not applied, which may be suitable for ideal channel simulations where phase distortion is minimal or not a concern.

3.TOOLS USED

3.1 MATLAB

Primary programming environment used for signal generation, simulation, and analysis.

3.2 5G Toolbox NR TM (MATLAB)

Provides functions and reference examples to design, simulate, and verify 5G NR physical layer systems as per 3GPP specifications**. NR Test Model (which you're already using in the project, e.g., TM1.1, TM3.1), Non-Real-Time Measurement.**

3.3 RF Toolbox / Communications Toolbox (Optional)

Assists in measuring RF metrics such as ACLR, EVM, and power spectrum.

3.4 3GPP Technical Specifications (TS 38.141-1/2)

Official reference documents for defining and verifying conformance test models and performance requirements.

4. METHODOLOGY

4.1 Model Selection and Configuration:

Selected test models TM1.1 (single antenna port, single layer) and TM3.1 (multi-antenna, multi-layer) based on 3GPP TS 38.141.

Defined carrier configurations including subcarrier spacing, bandwidth, and NR numerology.

4.2 Waveform Generation:

Used MATLAB 5G Toolbox to generate standard-compliant downlink waveforms.

Configured modulation schemes (QPSK, 16-QAM, 64-QAM) and resource grids accordingly.

4.3 Transmitter Simulation:

Simulated waveform transmission through a baseband model.

Incorporated channel impairments to mimic real-world conditions (e.g., AWGN, fading).

4.4 Signal Analysis:

Measured Error Vector Magnitude (EVM), Adjacent Channel Leakage Ratio (ACLR), and power spectral density (PSD).

Used Signal Analyzer App for spectral visualization and MATLAB scripts for numerical analysis.

4.5 Compliance Check:

Compared results with 3GPP TS 38.141 performance requirements.

Verified waveform characteristics like spectral flatness and bandwidth occupancy.

4.6 Result Interpretation:

Analyzed signal behavior under different modulations.

Identified performance deviations and interpreted their causes.

5. RESULTS AND ANALYSIS:

5.1 TM3.1 Results:

Slight EVM degradation observed with 64-QAM at higher layers.

ACLR performance was within limits but closer to threshold under multi-layer transmission.

Modulation complexity influenced spectral efficiency and robustness.

5.2 Comparative Analysis:

QPSK showed the highest robustness with minimal EVM and ACLR deviations.

16-QAM provided a balance between performance and complexity.

64-QAM demonstrated increased vulnerability to channel impairments.

Develop 5G NR Test models

5G NR Test Models using MATLAB 5G Toolbox MODULATION, DEMODULATION of 5G NR-TM WAVEFORM USING MATLAB, (TM1.1)

3GPP standards and identify deviations under different modulation schemes:

NR TM Inputs (FR1) **I**

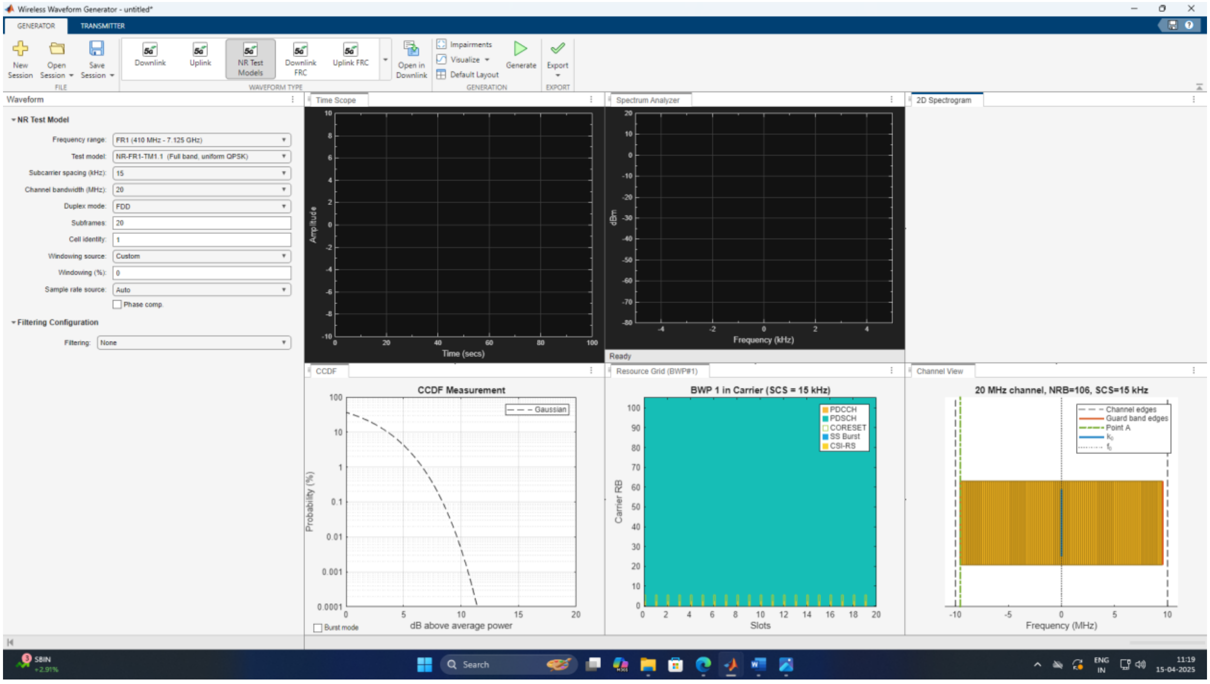

Fig 5.1 – NR TM Inputs (FR1)

NR TM Input Time scope

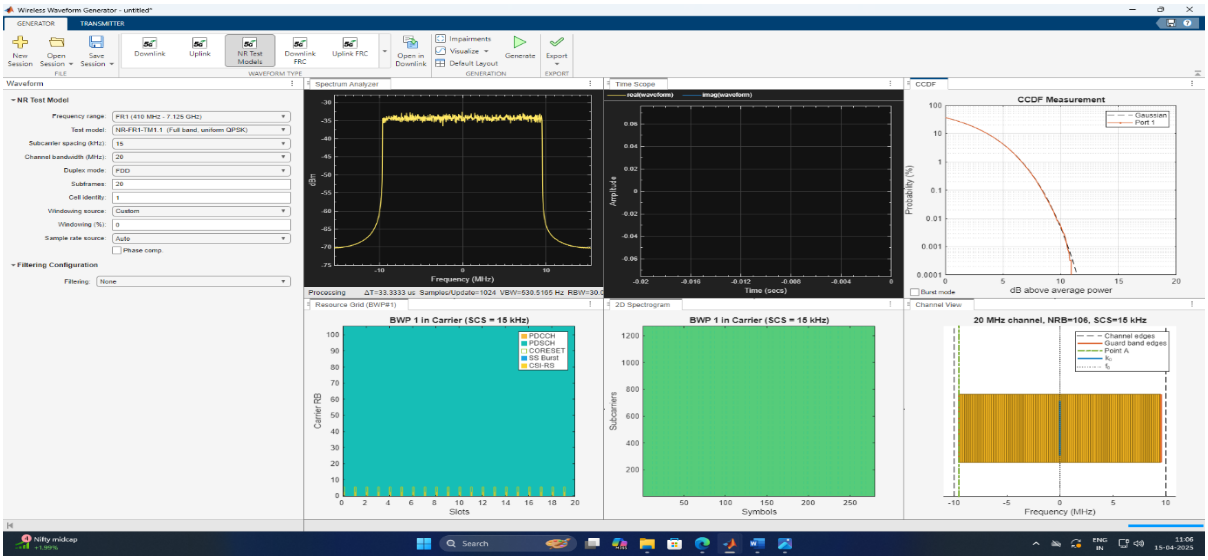

Fig 5.2 – NR TM Input Time scope

OUTPUT

FR1 = NR TM Input Time scope REAL AND IMAG (WAVEFORM)

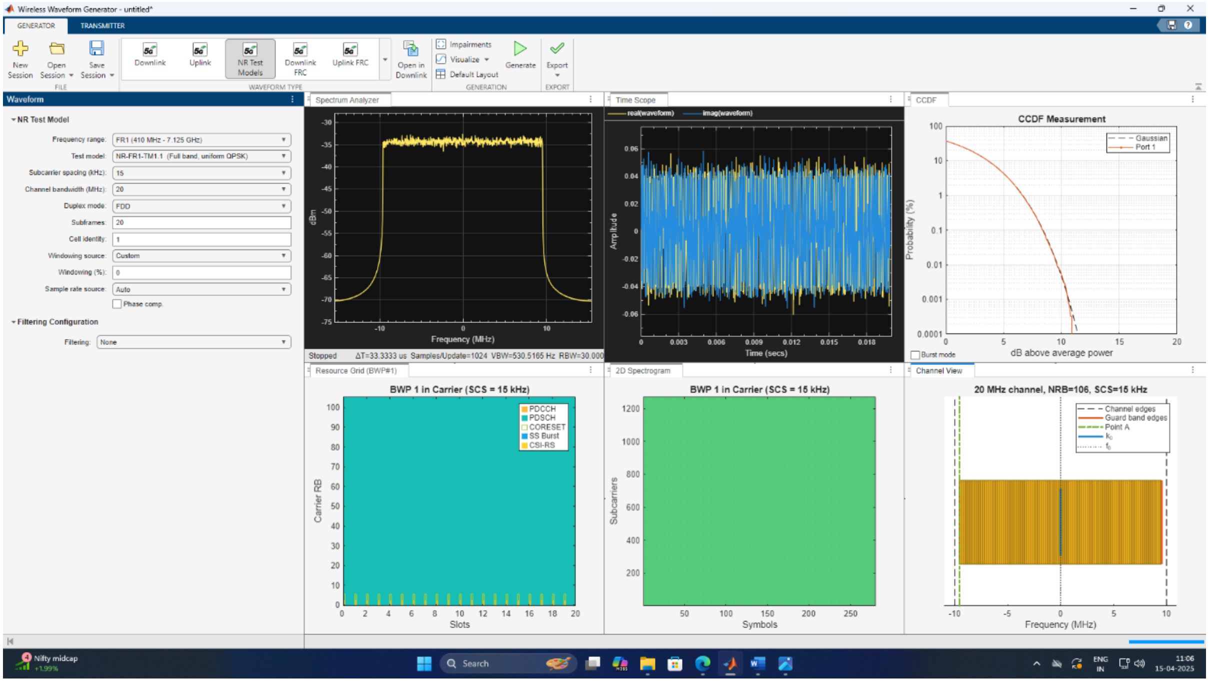

Fig 5.3 – NR TM Input Time scope REAL AND IMAG (WAVEFORM)

FR2

NR TM Input (FR2)

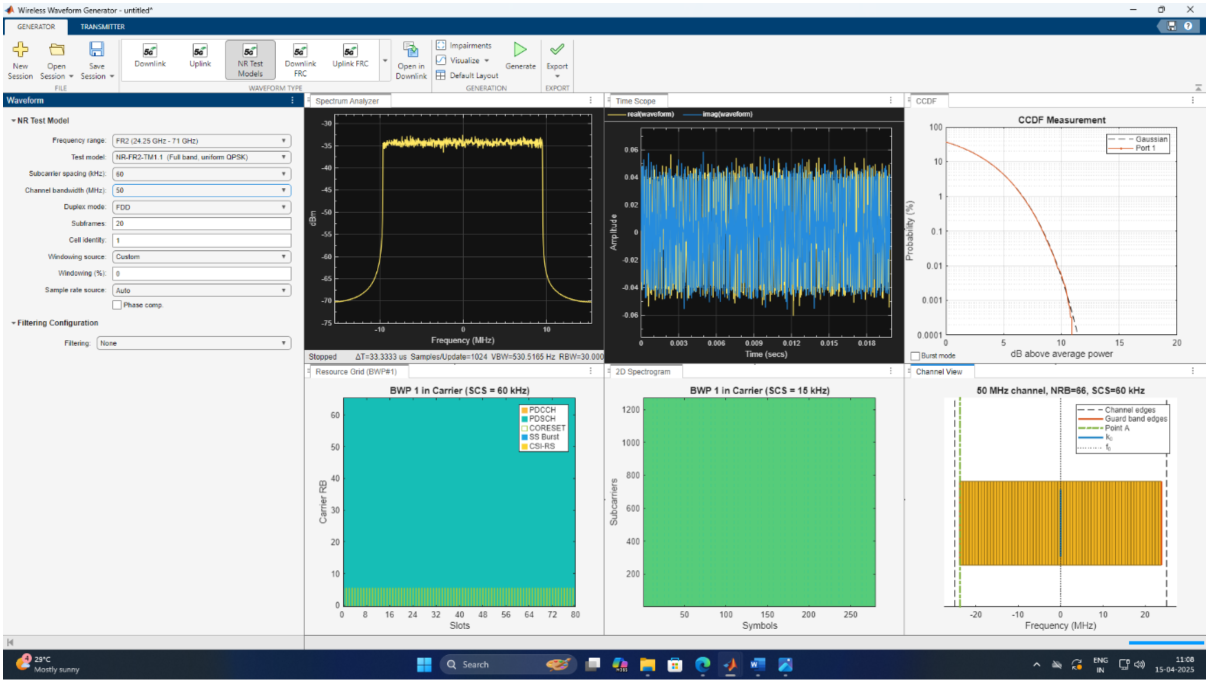

Fig 5.4 – NR TM Input (FR2)

- **OUTPUT**

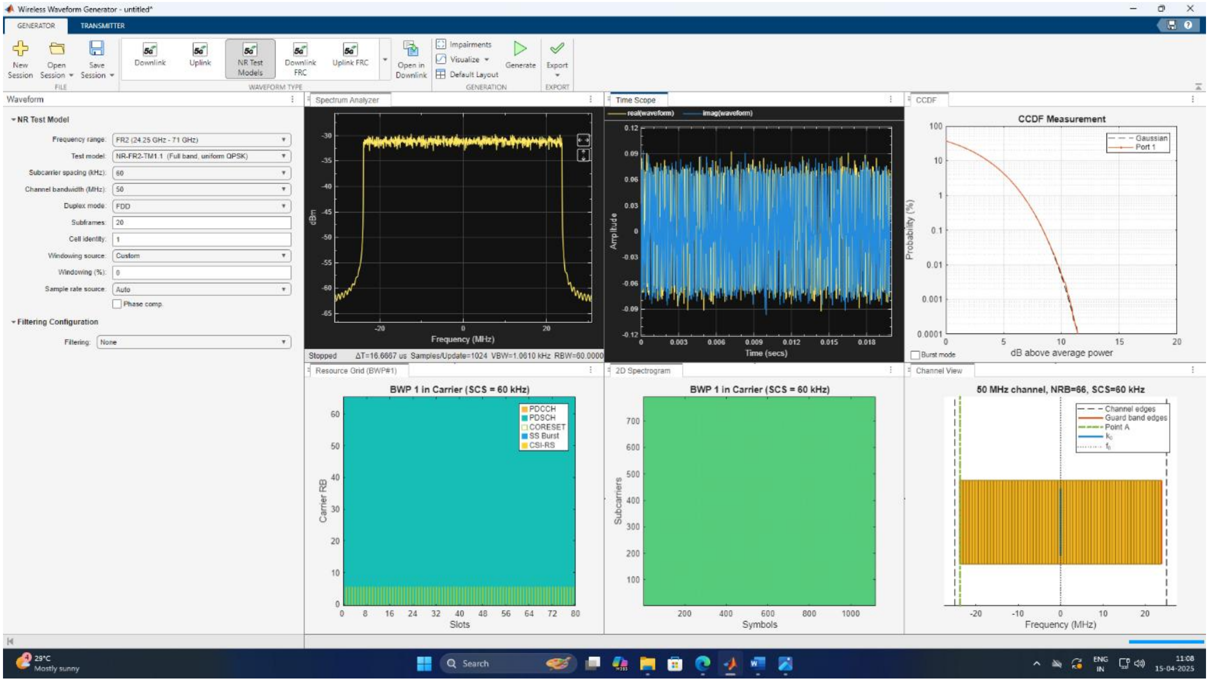

Fig 5.5– NR TM OUTPUT

SIMULINK Model Structure code: Modeling and Testing an NR RF Transmitter

Code for Simulink model structure

```
modelName = 'NRModelingAndTestingRFTransmitterModel';
open_system(modelName);
```

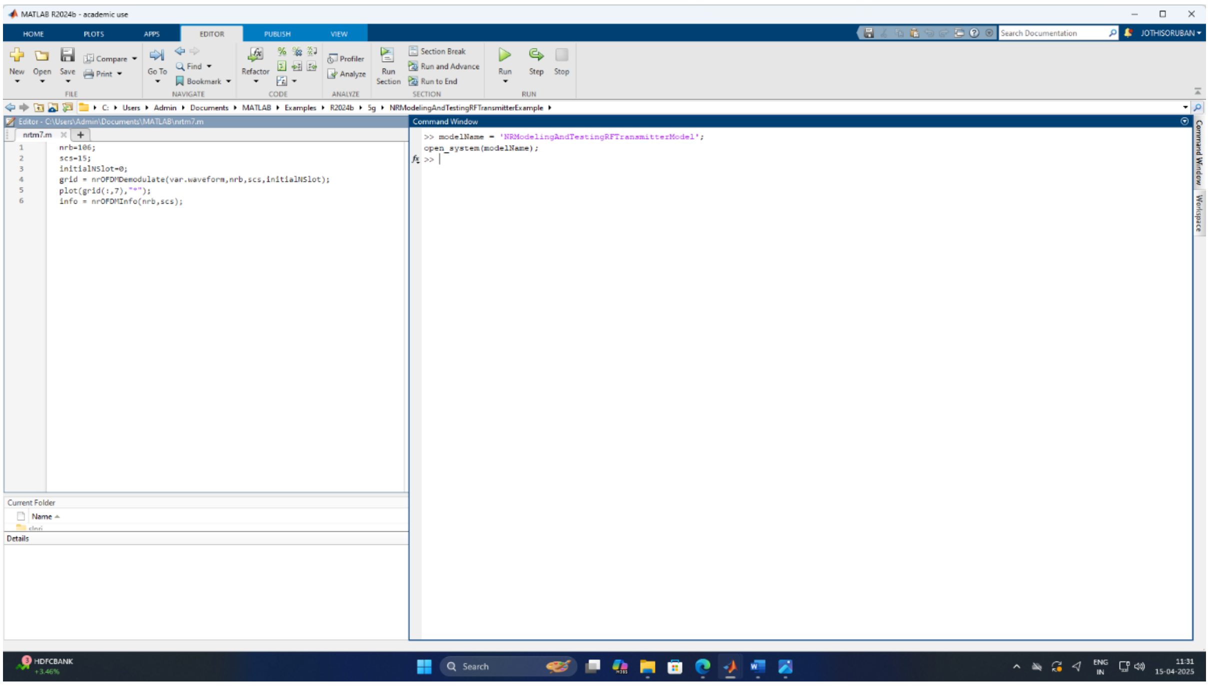

Fig 5.6– SIMULINK Model Structure code

SIMULINK Model Structure 1

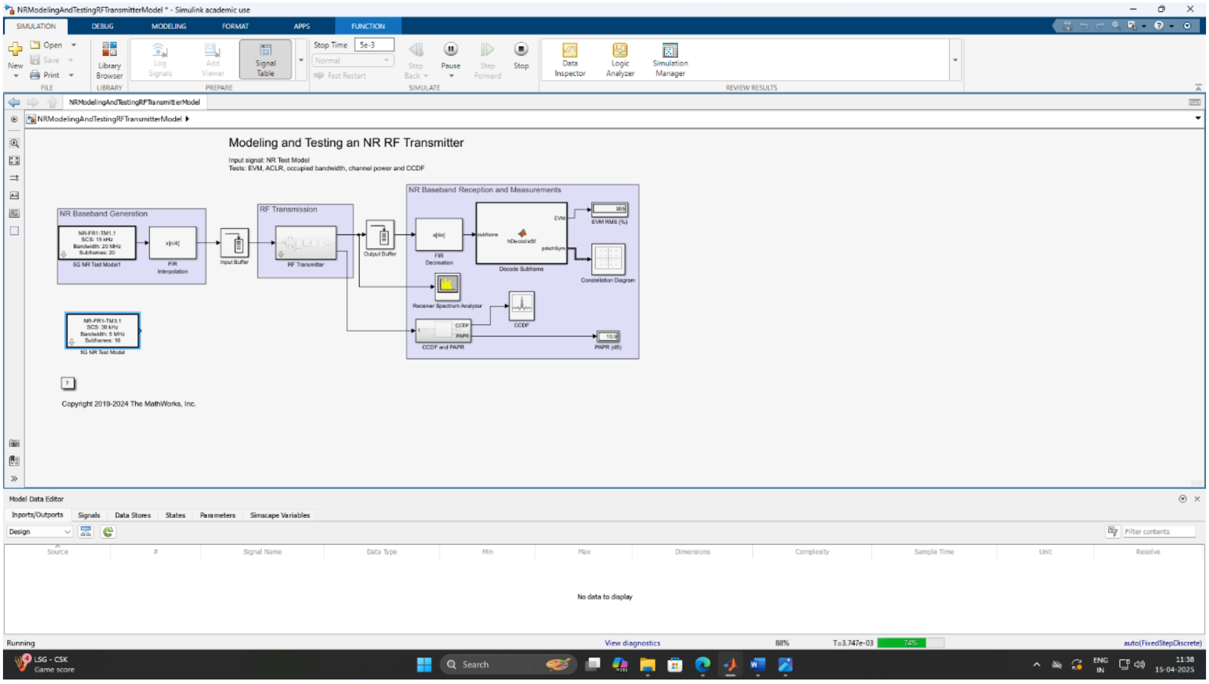

Fig 5.7 – Modeling and testing an NR

```
%hDecodeSf Subframe decodification and EVM calculation
%   [EVM,PDSCHSYM] = hDecodeSf(SUBFRAME) calls the function which
decodes
%   the subframe SUBFRAME. It returns the decoded symbols
%   PDSCHSYM and the average EVM.

%   Copyright 2019-2021 The MathWorks, Inc.

function [EVM,pdschSym] = hDecodeSf(subframe)

   coder.extrinsic('hDecodeSubframe');

   % Create count to track number of current transmitted subframe
   persistent count;
   % Create persistent variables for current and previous subframes
   persistent subframe1
   persistent subframe2
```

```
    % Specify output type
    pdschSym = complex(0,0);
    EVM = 0; %#ok<NASGU>

    % Initialize the persistent variables
    if isempty(count)
        count = -2;
        subframe2 = subframe;
        subframe1 = 0;
        subframes = 0;
    else
        subframe1 = subframe2;
        subframe2 = subframe;
        subframes = [subframe1; subframe2];
    end

    % Get the number of the current transmitted subframe
    numberFrames = 10;
```

CODE FOR DECODE :

```
subframeNo = mod(double(count),numberFrames);

    % Decode a length of two subframes to account for time delays
    if count > -1
        EVM3GPP = false;
        [evm,pdschsym]  =
hDecodeSubframe(subframeNo,subframes,count,EVM3GPP);
        pdschSym(:) = pdschsym;
        EVM = evm;
    else
        pdschSym(:) = NaN;
```

```
      EVM = NaN;
   end

   % Increment counter
   count = count + 1;

end
```

SIMULINK Model Structure 2

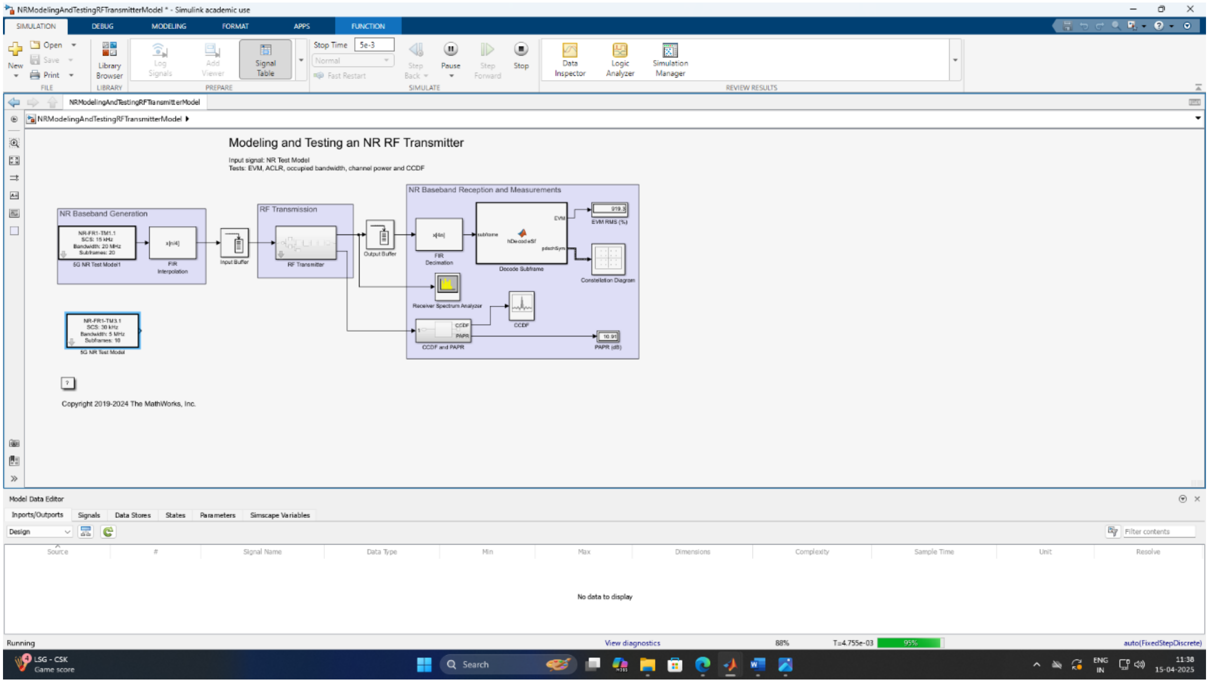

Fig 5.8 – Modeling and Testing an changing NR baseband Generation

- **RF transmitter SIMULINK Model:**

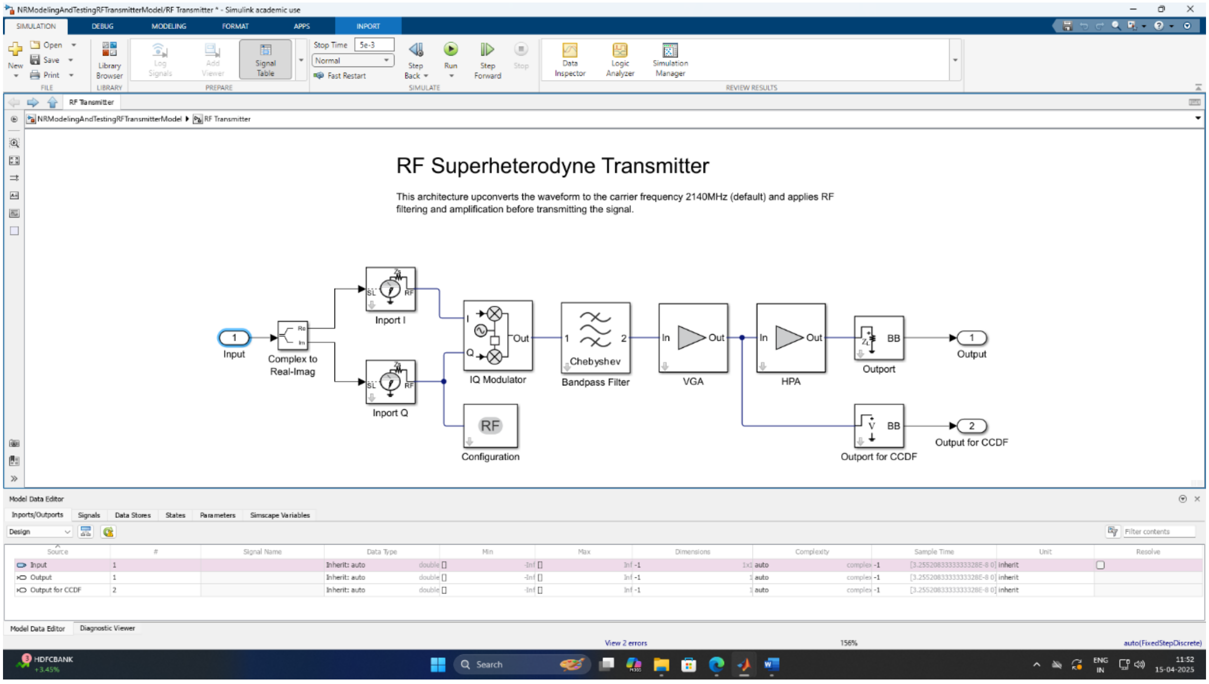

Fig 5.9– RF transmitter SIMULINK Model

- **OUTPUT OF NR Frequency bandwidth**

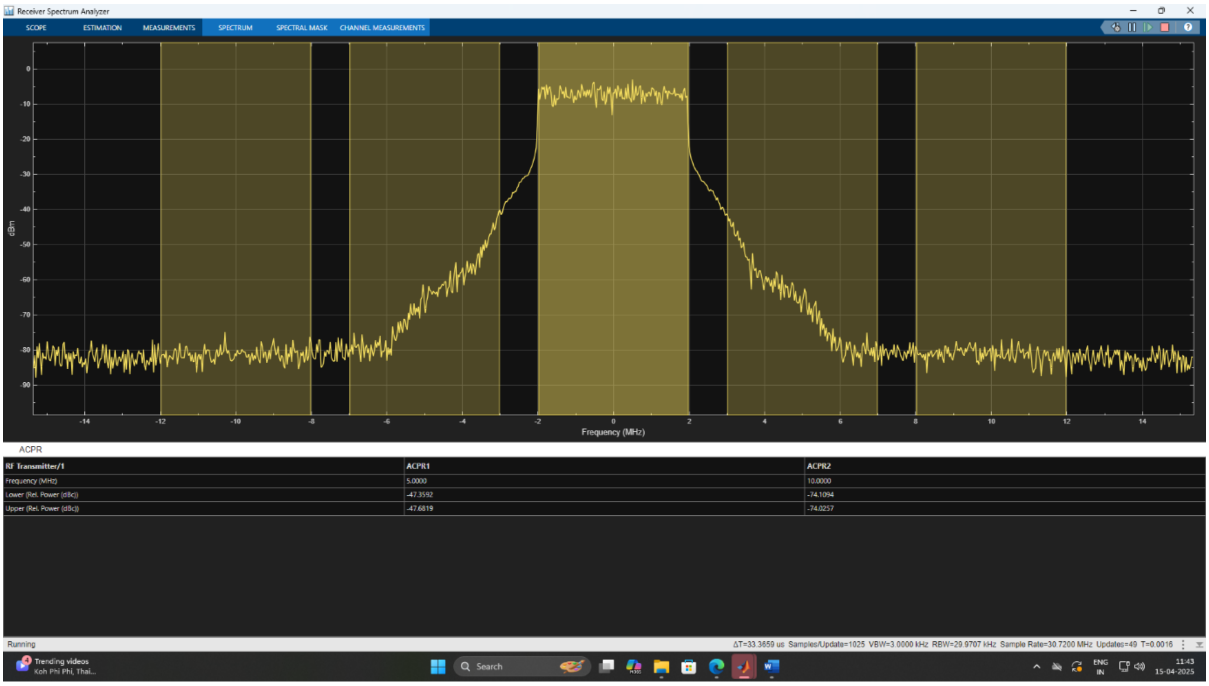

Fig 5.10– OUTPUT OF NR Frequency bandwidth

Consolidation Diagram

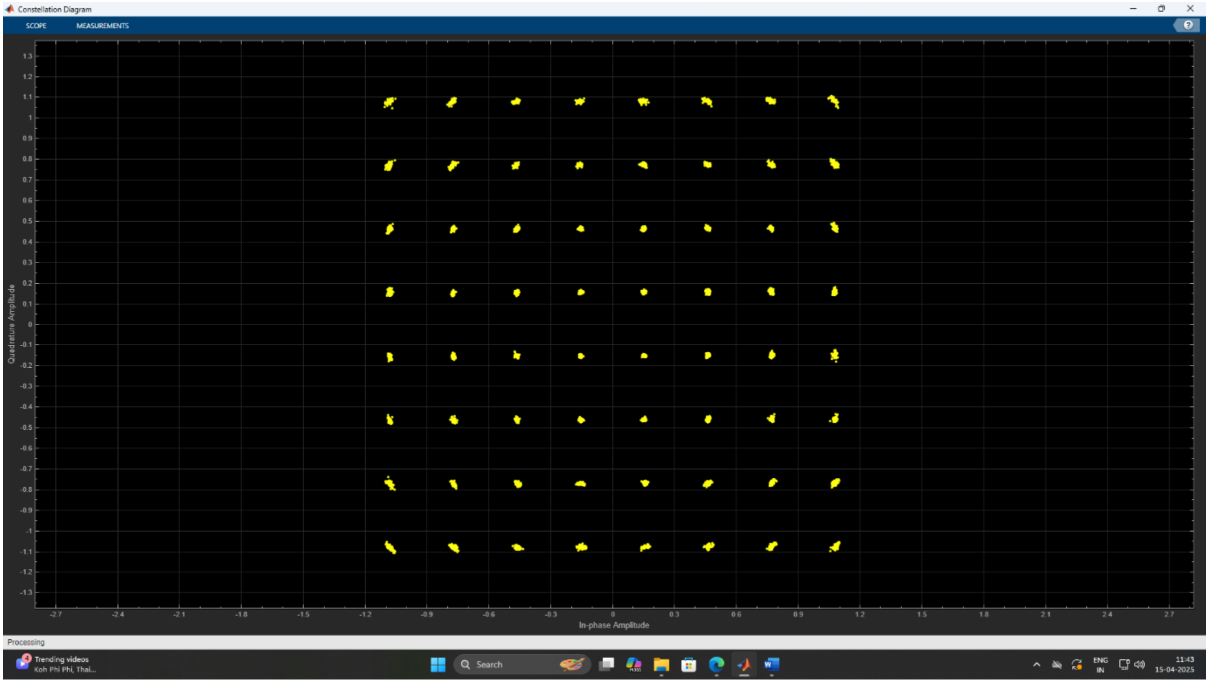

Fig 5.11 – Consolidation Diagram

Complementary cumulative distribution function(CCDF):

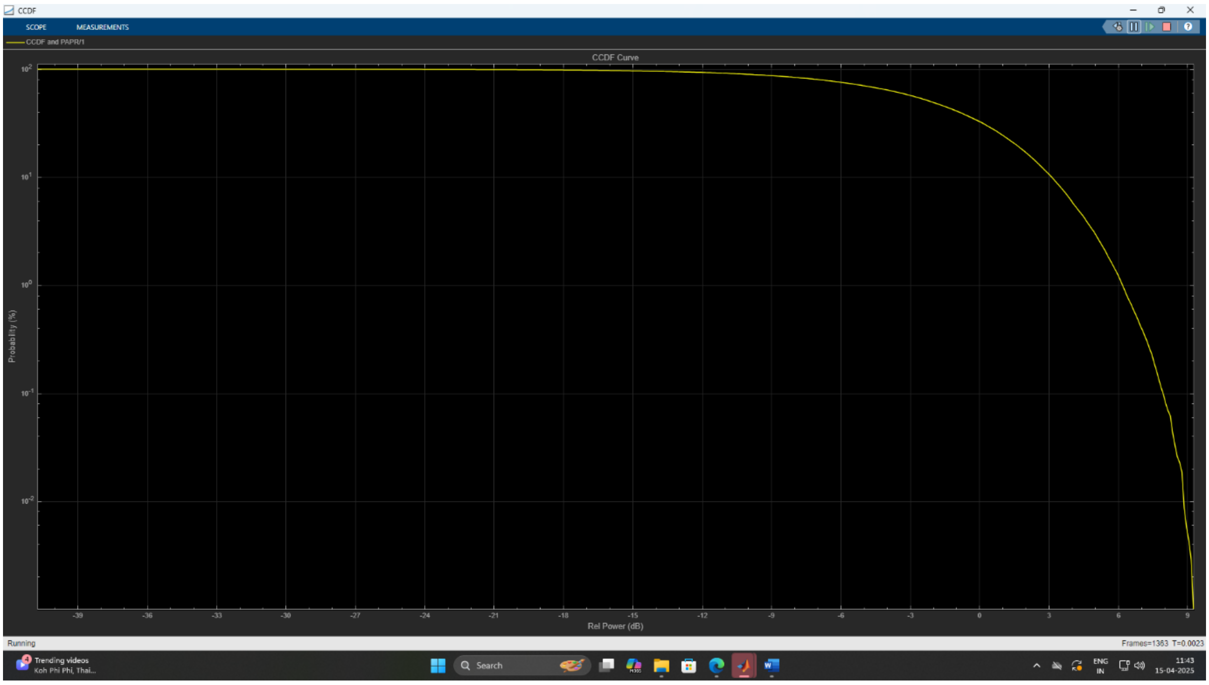

Fig 5.12 – Complementary cumulative distribution function(CCDF)

EVM per (Slot number, OFDM symbol number, Subcarrier Number):

Fig 5.13– EVM per (Slot number, OFDM symbol number, Subcarrier Number):

- **NR TEST MODEL CHANGING PARAMETERS 1:**

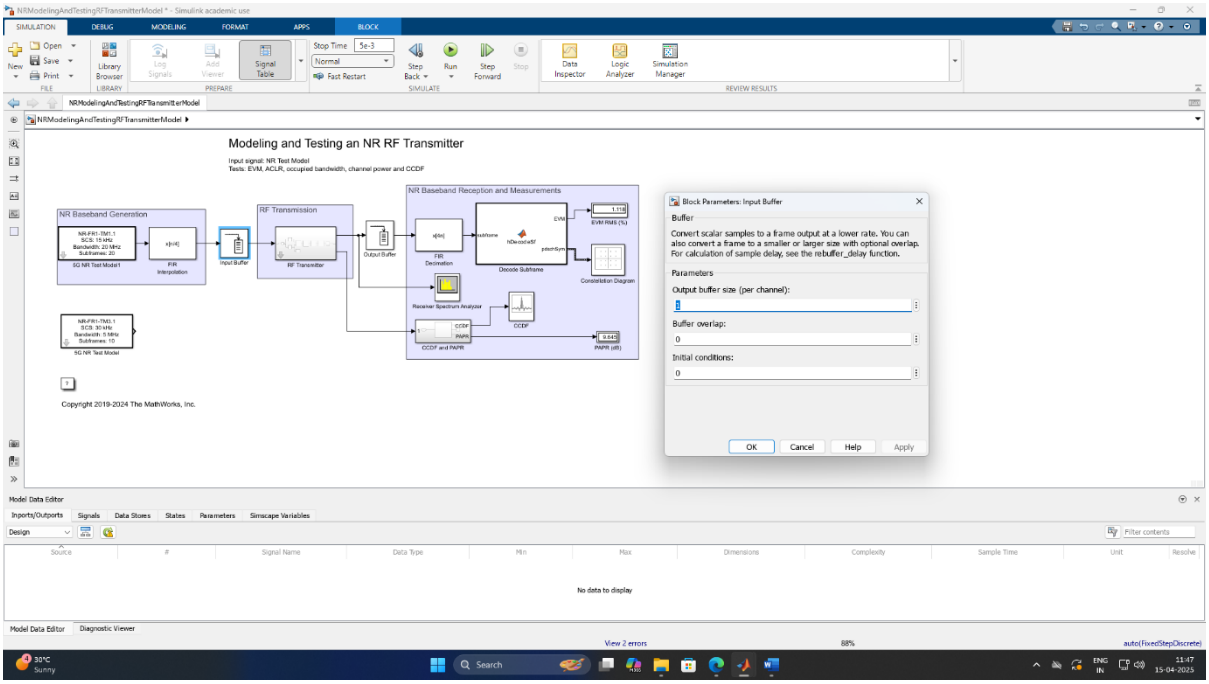

Fig 5.14- NR TEST MODEL CHANGING PARAMETERS 1

NR TEST MODEL CHANGING PARAMETERS 2

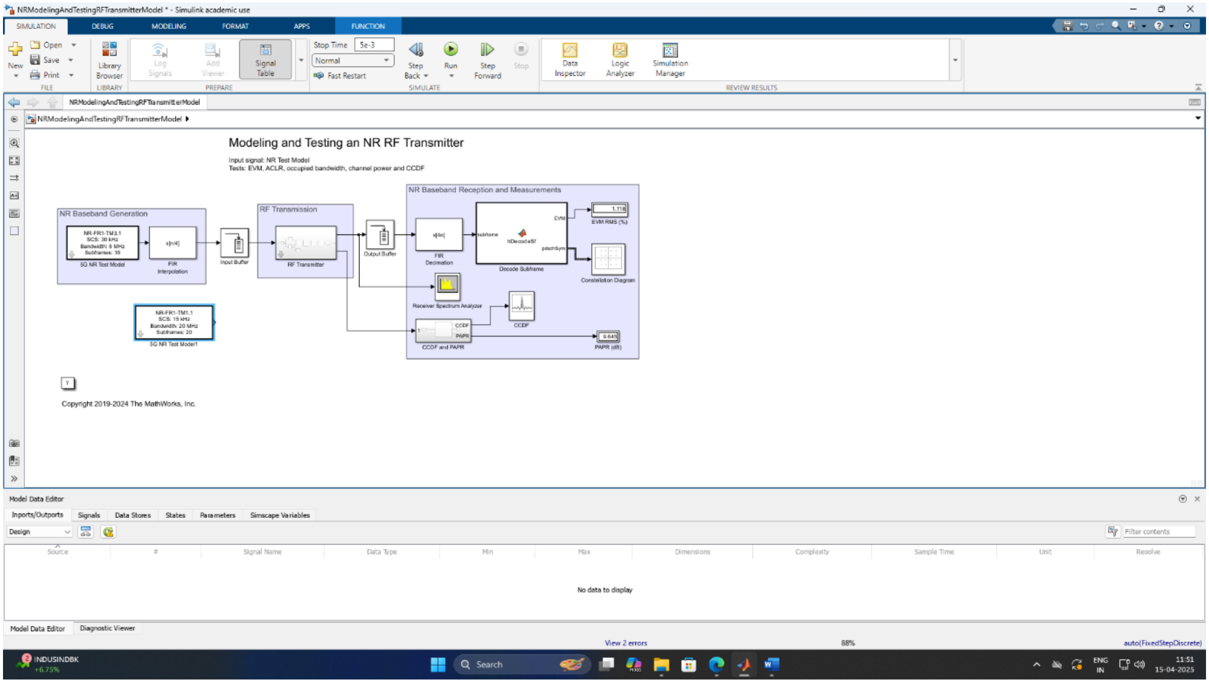

Fig 5.15 – NR TM

Generating waveform for modulation :

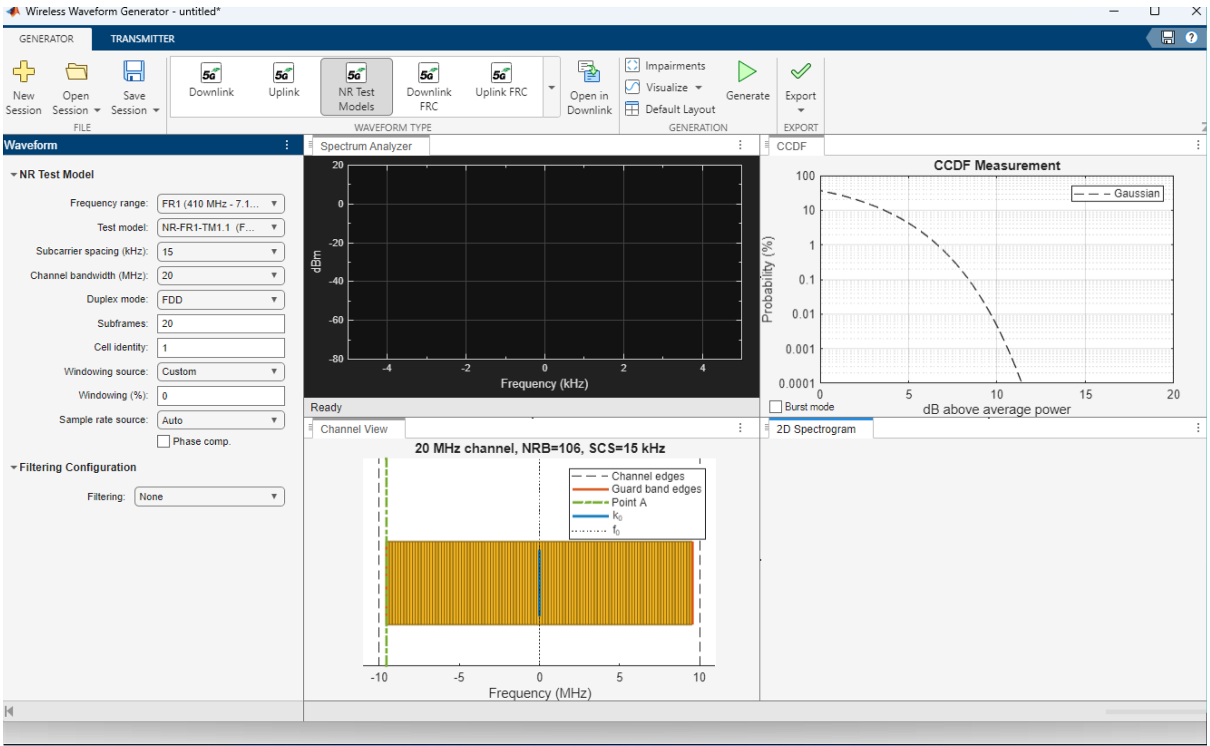

Fig 5.16– Generating waveform for modulation

Generating waveform for modulation using NR Test model

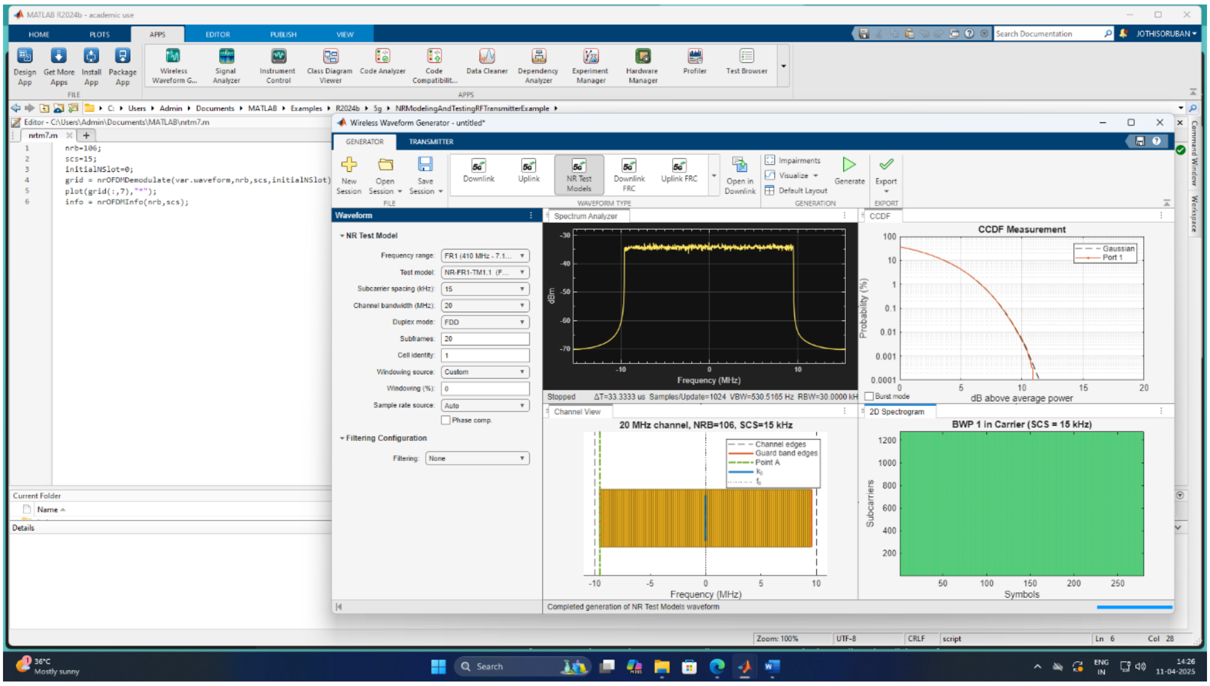

Fig 5.17 – Generating waveform for modulation using NR Test model

- **DEMODULATION of 5G NR-TM WAVEFORM USING MATLAB**

Demodulation is the process of recovering the transmitted information from the received waveform. In the context of 5G NR Test Models (TMs), demodulation validates the integrity and compliance of downlink signals (e.g., TM1.1, TM3.1) by verifying that transmitted data can be correctly decoded under real or simulated channel conditions.

Steps in 5G NR Demodulation using Export to Workspace:

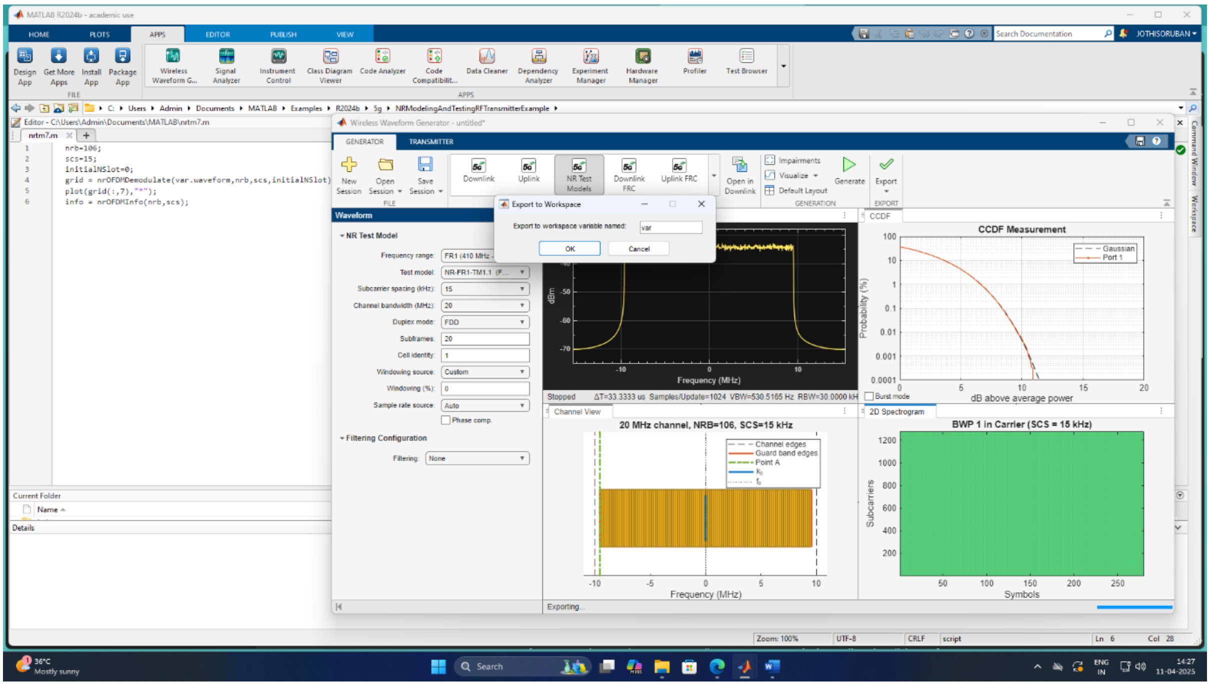

Fig 5.19– 5G NR Demodulation using Export to Workspace

nrb=106;

scs=15;

initialNSlot=0;

grid = nrOFDMDemodulate(var.waveform,nrb,scs,initialNSlot);

plot(grid(:,7),"*");

info = nrOFDMInfo(nrb,scs);

5G NR Demodulation OUTPUT

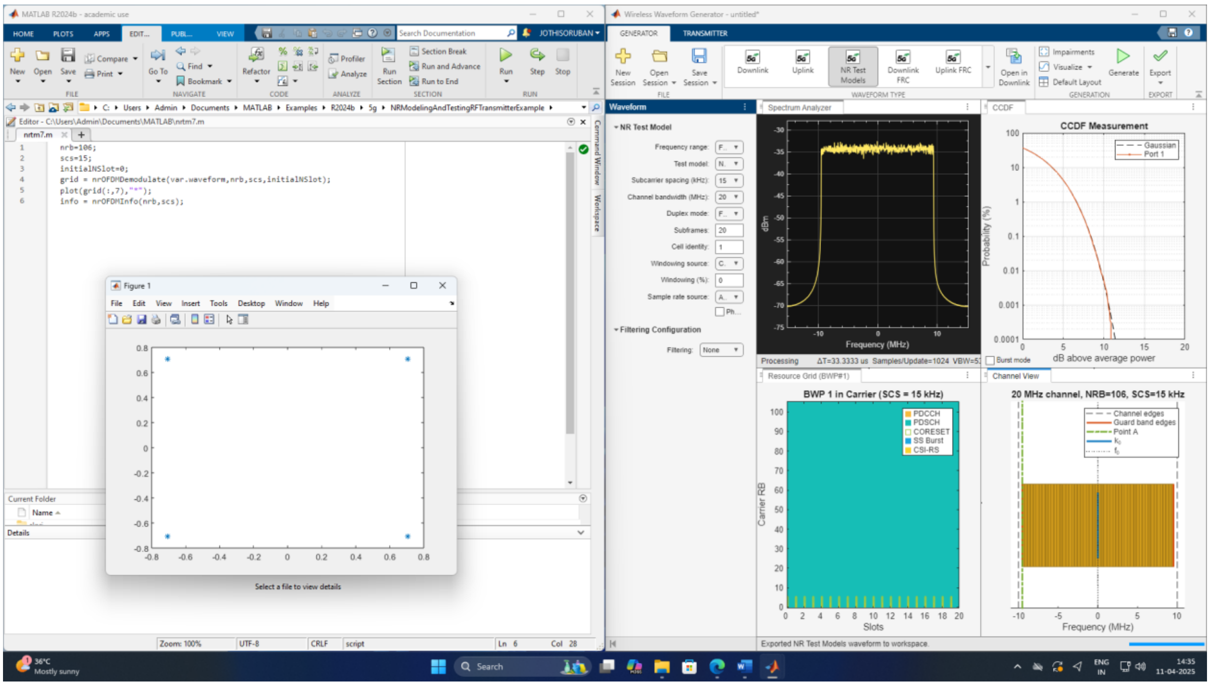

Fig 5.20– 5G NR Demodulation OUTPUT

6. CONCLUSION:

The project successfully demonstrated the development and evaluation of 5G NR test models TM3.1 using MATLAB. The generated waveforms adhered to 3GPP standards and revealed how modulation schemes influence transmitter performance. The findings contribute to understanding compliance challenges in real-world transmitter design and provide a foundation for further 5G NR physical layer validation and optimization.

Appendices

Appendix A: MATLAB Code Snippet for TM1.1 Waveform Generation

matlab

CopyEdit

```
nrb = 106;
scs = 15;
initialNSlot = 0;
waveform = nrWaveformGenerator(cfg);
grid = nrOFDMDemodulate(waveform, nrb, scs, initialNSlot);
plot(grid(:,7), '*');
info = nrOFDMInfo(nrb, scs);
```

Appendix B: Parameters for TM1.1 Configuration

Parameter	Value
Frequency Range	FR1 (410 MHz – 7.125 GHz)
Test Model	NR-FR1-TM1.1
Subcarrier Spacing	15, 30, 60 kHz
Channel Bandwidth	20 MHz
Duplex Mode	TDD / FDD
Subframes	20
Cell Identity	1
Windowing (%)	0

Appendix C: Acronyms and Abbreviations

Acronym	Full Form
5G NR	5G New Radio
TM	Test Model
QPSK	Quadrature Phase Shift Keying
QAM	Quadrature Amplitude Modulation
EVM	Error Vector Magnitude
ACLR	Adjacent Channel Leakage Ratio

Acronym	**Full Form**
AWGN	Additive White Gaussian Noise
PSD	Power Spectral Density
CCDF	Complementary Cumulative Distribution Function

References

1. 3GPP TS 38.141-1 V16.5.0 – *NR; Base Station Conformance Testing; Part 1: Conducted*, 3GPP, December 2020.

   ↳ Specifies the requirements for base station transmitter conformance including TM1.1 and TM3.1.

2. 3GPP TS 38.141-2 V16.5.0 – *NR; Base Station Conformance Testing; Part 2: Radiated*, 3GPP, December 2020.

   ↳ Used for understanding over-the-air testing procedures and radiated signal requirements.

3. MathWorks Inc. – *MATLAB R2023a Documentation*. https://www.mathworks.com/help/matlab

   ↳ MATLAB is a numerical computing environment used for signal processing, visualization, simulation, and modelling in this project.

4. MathWorks Inc. – *5G Toolbox Documentation*. https://www.mathworks.com/help/5g

   ↳ Provides built-in functions for 5G waveform generation, demodulation, and compliance testing.

5. MathWorks Inc. – *Simulink for Wireless Communications*, 2023.

   ↳ Graphical modelling platform used for RF transmitter simulation and system-level design.

6. AMTLAB Technical Manual, 2023.

   ↳ Real-time lab platform for hands-on training and simulation of 5G signal scenarios, used to validate MATLAB results against hardware configurations.

7. Rappaport, T. S. – *Wireless Communications: Principles and Practice*, 2nd ed., Prentice Hall, 2002.

   ↳ A foundational resource for understanding wireless signal theory, fading channels, and modulation techniques.

   Rappaport, T. S. – *Millimetre Wave Wireless Communications*, Pearson Education, 2014. ↳ Supports theoretical aspects of FR2 frequencies and advanced 5G signal modelling.