SPECTRAL ANALYSIS AND 5G-NR UPLINK/DOWNLINK WAVEFORM ANALYSIS USING PLUTOSDR.

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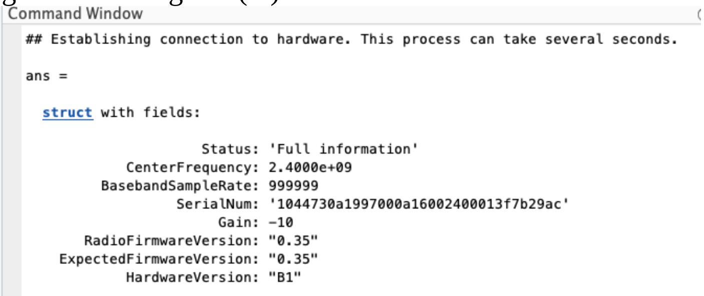
Introduction

This report provides the results of examining the transmission and receiving stages such as the spectral analysis, IQ data, power measurement plots when using a PlutoSDR with different parameters and 5G-NR uplink and downlink. Use cases and features of 5G NR, such as PDSCH, PDCCH, PBCH, PSS, SSS, and CSI-RS signals, mmWave frequencies, beamforming, and BWPs will be discussed in this report as well as the comparison between physical layer differences between LTE and 5G-NR.

The functions sdrtx and sdrrx were put into Matlab to get create transmitter system object for radio hardware and receiver system object for radio hardware. Using the info object function, I got this information about them. [1]

Figure 1 showing info(tx)

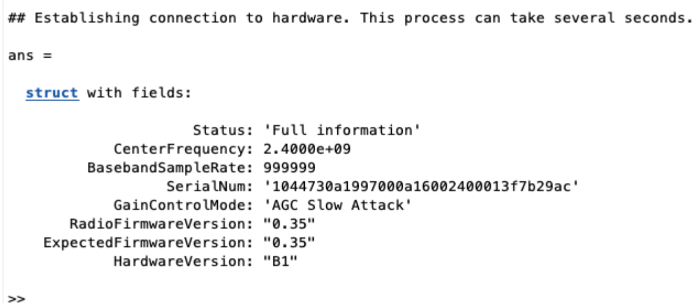


```
Command Window
## Establishing connection to hardware. This process can take several seconds.

ans =

  struct with fields:

                   Status: 'Full information'
          CenterFrequency: 2.4000e+09
       BasebandSampleRate: 999999
                SerialNum: '1044730a1997000a16002400013f7b29ac'
                     Gain: -10
    RadioFirmwareVersion: "0.35"
 ExpectedFirmwareVersion: "0.35"
          HardwareVersion: "B1"
```



```
## Establishing connection to hardware. This process can take several seconds.

ans =

  struct with fields:

                   Status: 'Full information'
          CenterFrequency: 2.4000e+09
       BasebandSampleRate: 999999
                SerialNum: '1044730a1997000a16002400013f7b29ac'
          GainControlMode: 'AGC Slow Attack'
     RadioFirmwareVersion: "0.35"
  ExpectedFirmwareVersion: "0.35"
          HardwareVersion: "B1"

>>
```

Figure 2 showing info(rx)

Figures 1 and 2 above show the serial number, the Tx gain, gain control mode, radio firmware version and hardware version of PlutoSDR which is basically the structure with field.

Task 1

Using spectral analysis Simulink model, Channel 1 at 2.412 GHz and Channel 2 at 2.417 GHz bands were measured. The IQ data is shown in Figure 3, PSD in Figure 4, and spectrogram of the received WIFI signal in Figure 5 for Channel 1 is shown below.

Figure 3 showing the IQ data of Channel 1 at 2.412 GHz

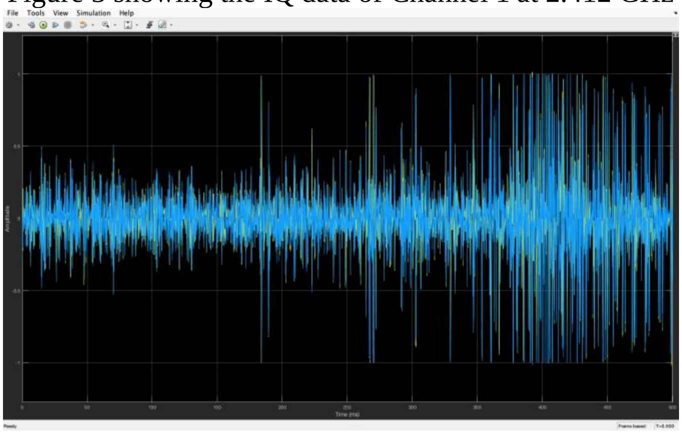


Figure 4 showing the PSD of Channel 1 at 2.412 GHz

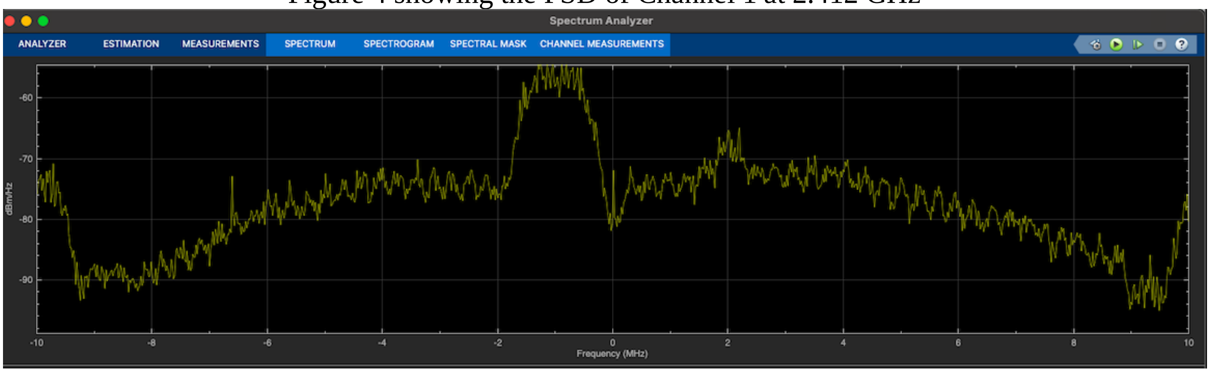
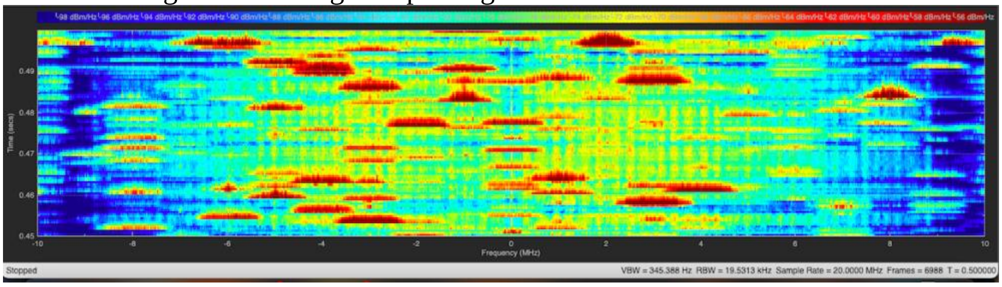


Figure 5 showing the spectrogram of Channel 1 at 2.412 GHz



The amplitude in the IQ data of Channel 1 is observed to increase more over time.

The PSD graph in Figure 4 shows frequency selectivity where different frequency components of the signal experience varying levels of attenuation or distortion as they propagate through a communication channel. Therefore, some parts of the signal being weakened or distorted more than others. Power levels drop off towards the edges of the band.

The colours on the spectrogram in figure 5 represents the signal power levels over time. The red/orange indicate higher power levels which occur mostly between frequency of -6MHz and 5MHz. The blue/green colours indicate lower power levels. The OFDM spectrum shows distortion.

The IQ data is shown in Figure 6, PSD in Figure 7, and spectrogram of the received WIFI signal in Figure 8 for Channel 2 is shown below.

Figure 6 showing the IQ data of Channel 2 at 2.417 GHz

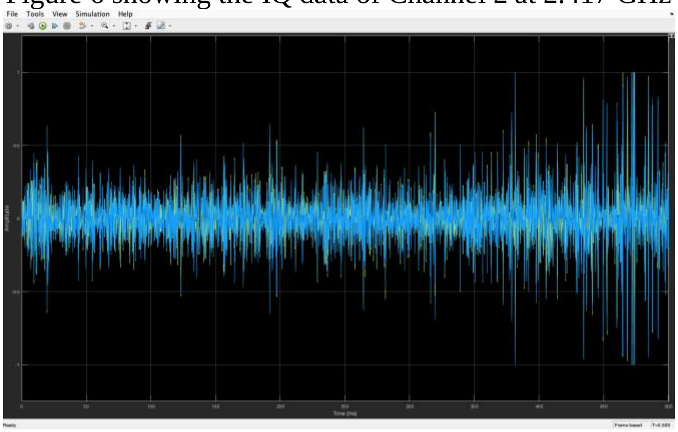


Figure 7 showing the PSD of Channel 2 at 2.417 GHz

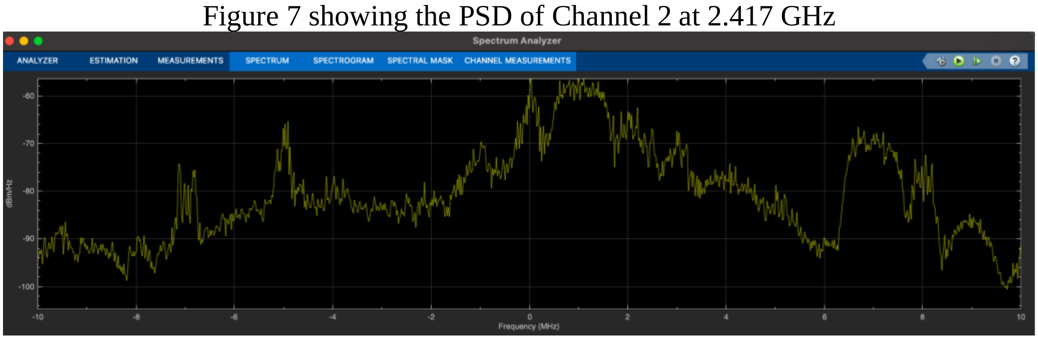
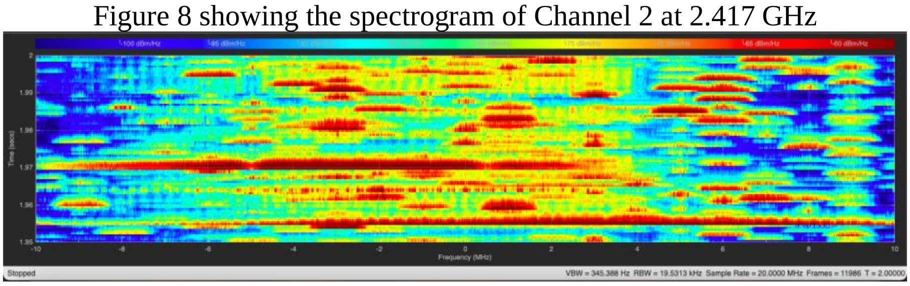


Figure 8 showing the spectrogram of Channel 2 at 2.417 GHz



The amplitude in the IQ data of Channel 2 seen in Figure 6 is observed to increase over time but not as frequent as Channel 1.

The PSD graph in Figure 7 shows more frequency selectivity than that of Channel 1. This could be caused by multipath fading where the signal can be reflected, refracted, or diffracted along multiple paths before reaching the receiver and channel dispersion.

The colours on the spectrogram in figure 8 represents the signal power levels over time. The red/orange higher power levels appear more frequent in Channel 2 than Channel 1 and the signal shows distortion, but not as distorted as Channel 1 as at the time 1.955 and 1.97, the power levels display a horizontal line.

Task 2

In this section, a signal was transmitted at a frequency of $200\text{x}10^3$ and received. To create the sine wave source, dsp.sinewave was used, the centre frequency at Tx and Rx radio system object is $2.5\text{x}10^9$.

The first set of results gotten are for an amplitude of 0.6:

Figure 9 showing received power of received sine wave tone for baseband amplitude of 0.6

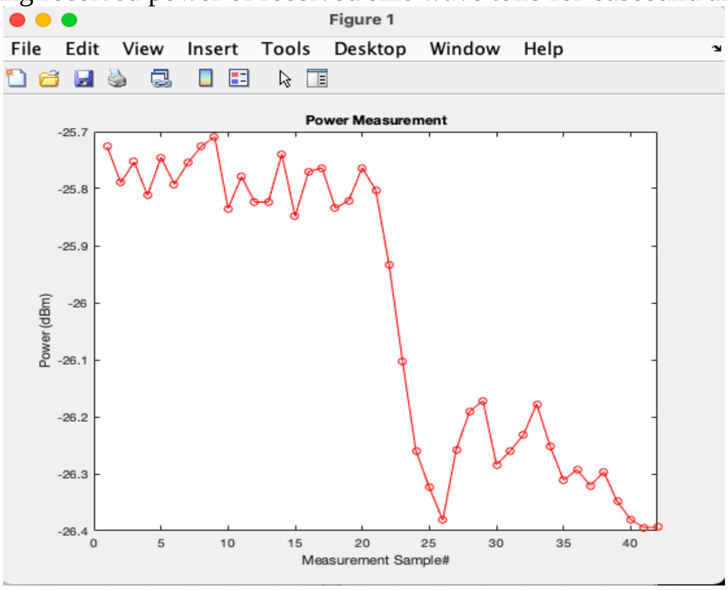


Figure 10 showing the PSD and spectrum for baseband amplitude of 0.6

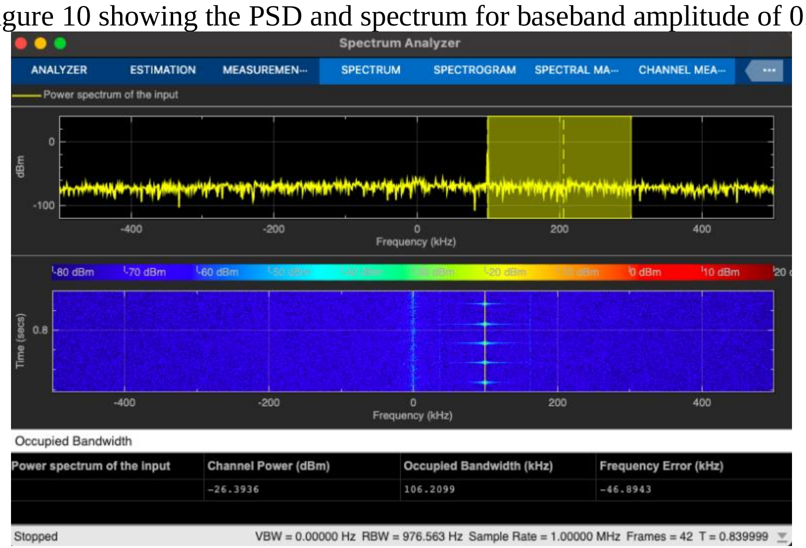
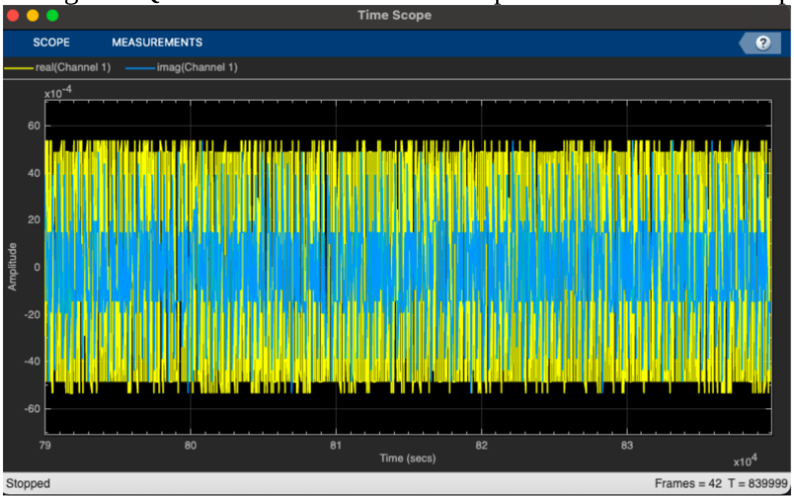


Figure 11 showing the IQ data received from time scope data for baseband amplitude of 0.6



In the power measurement graph, with a baseband amplitude of 0.6 in Figure 9 above, there are fluctuations in the received signal strength over time. The graph shows the received signal's power providing insights into the signal's stability and quality. The graph is a peak in signal strength at -25.72 dBm, then drops a bit still around the -25.72 – 25.76 range, followed by a sharp drop to -26.4 dBm around the 26th measurement sample. This rapid change in received signal power means that the signal has some level of instability in the wireless communication environment.

The channel power measurement is -26.3936 dBm seen in Figure 10.
The occupied bandwidth is 106.2099 KHz, which is the bandwidth containing a specified percentage (usually 99%) of the total transmitted power. The occupied bandwidth is relatively narrow compared to the baseband sample rate of 1 MHz, meaning that the sine wave signal is well confined within the specified frequency range.

The frequency error of 46.8943 KHz represents the difference between the expected centre frequency of the received signal and the actual centre frequency. This error can be caused by inaccuracies in the transmitter or receiver oscillators or doppler shifts due to the relative motion between the transmitter and receiver.

Figure 12 showing received power of received sine wave tone for baseband amplitude of 1

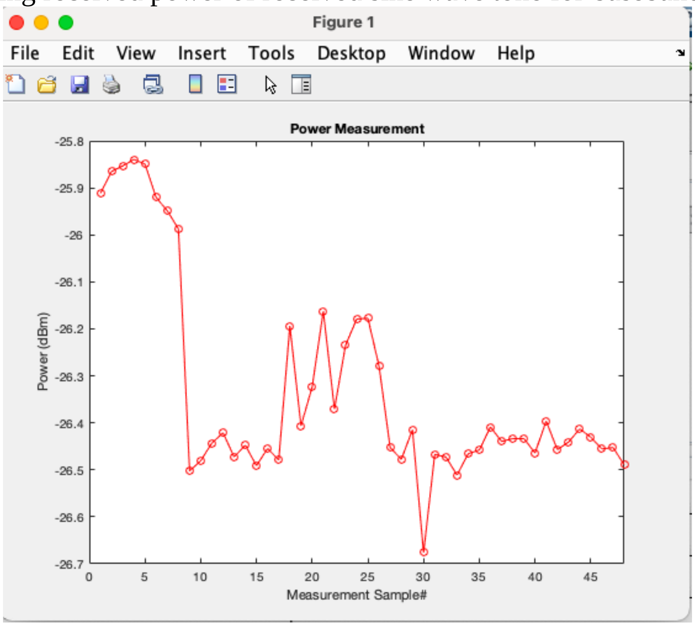


Figure 13 showing the PSD and spectrum for baseband amplitude of 1

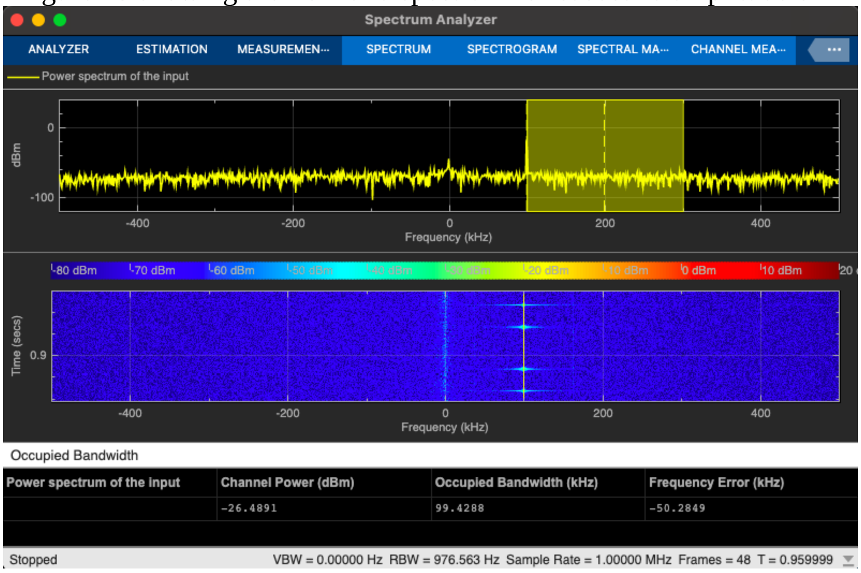
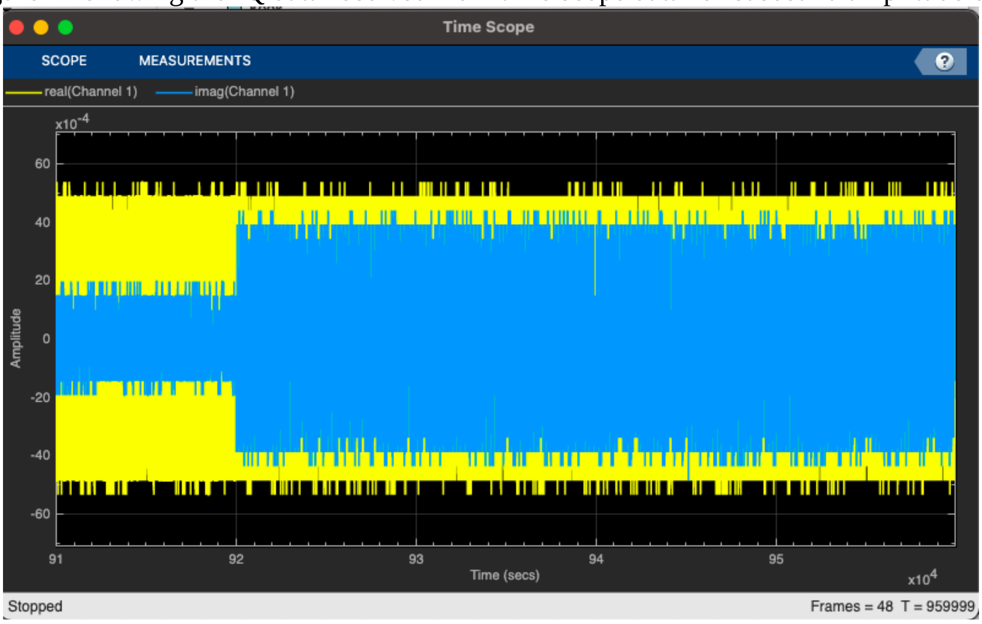


Figure 14 showing the IQ data received from time scope data for baseband amplitude of 1



In the power measurement graph for a baseband amplitude of 1, as seen in Figure 12, there is a sharp drop at 9 measurement samples from -26 to -26.5. There are more significant fluctuations at measurement samples 17.5 and 27 in the received signal strength over time compared to the baseband amplitude of 0.6. The graph exhibits a peak in signal strength at -25.82 dBm. There is a low peak at -26.7 dBm around the 30th measurement sample. This rapid change in received signal power suggests that the signal has some instability in the communication environment.

The channel power measurement is -26.4891 dBm, as seen in Figure 13. This is slightly lower compared to the 0.6 baseband amplitude. The occupied bandwidth is 99.4288 KHz. The frequency error is -50.2849 KHz is higher than that of the 0.6 baseband amplitude which means this has more instability.

Task 3

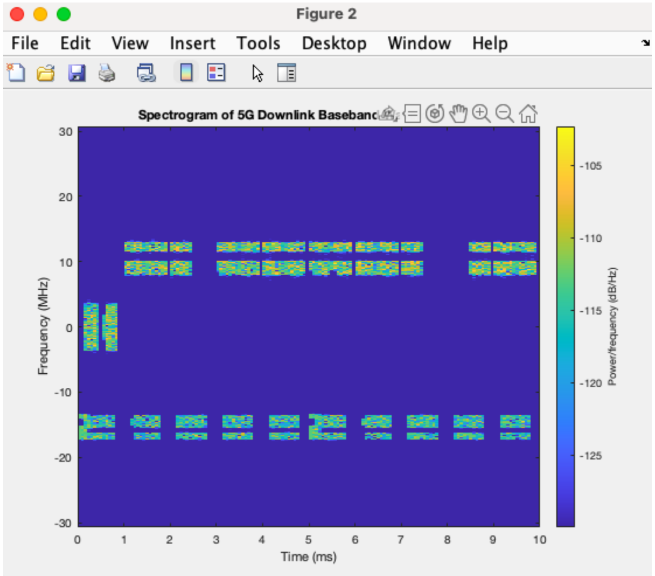


Figure 15a showing the Spectrogram of 5G Downlink Waveform at Tx

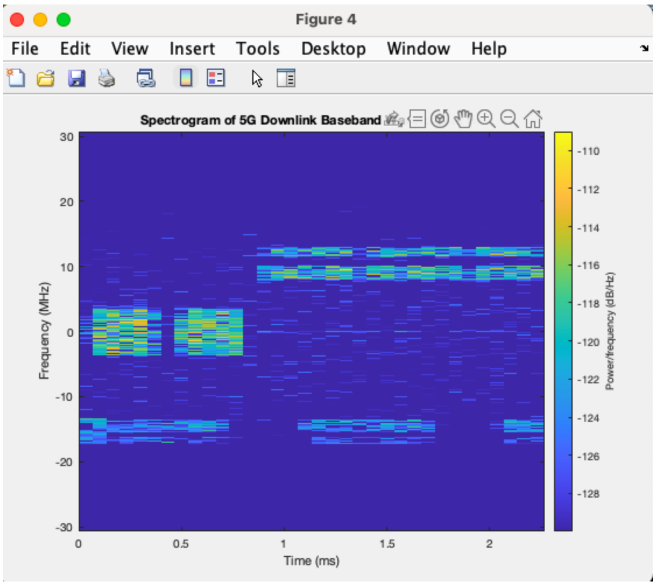
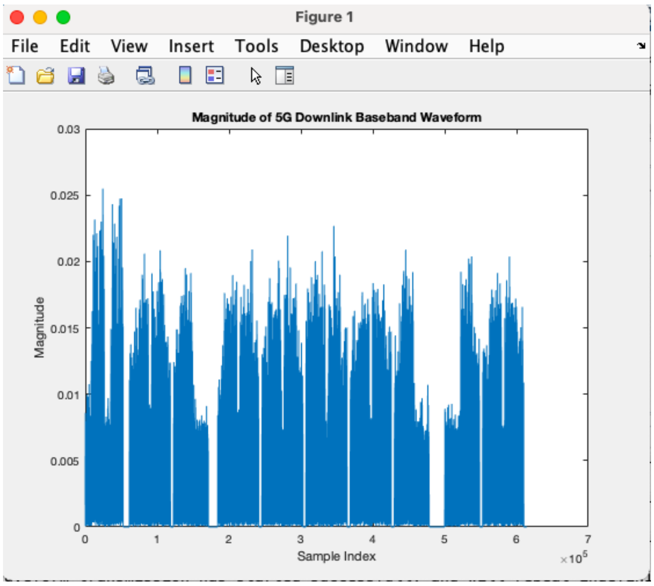


Figure 15b showing the Spectrogram of 5G Downlink Waveform at Rx

Both spectrograms in Figure 15a and 15b above show the time-frequency representation of the 5G downlink waveform. They show the distribution of power across time and frequency, the presence the channels and signals (PDSCH, PDCCH, PBCH, PSS, SSS, CSI-RS), and the time-frequency patterns of reference signals (DM-RS and PT-RS). The Rx waveform has lower signal power levels compared to the transmitted waveform due to propagation losses, path loss, and other factors affecting the signal as it travels through the wireless channel. As seen, the Rx plot is faded compared to the Tx plot.
The received waveform includes noise and interference from sources causing the additional patterns or speckles that are not in the Tx plot.
Multipath effects, cause time delays and frequency-selective fading which cause the smearing in the Rx spectrogram.

Figure 16a showing the Magnitude of 5G Downlink Baseband Waveform



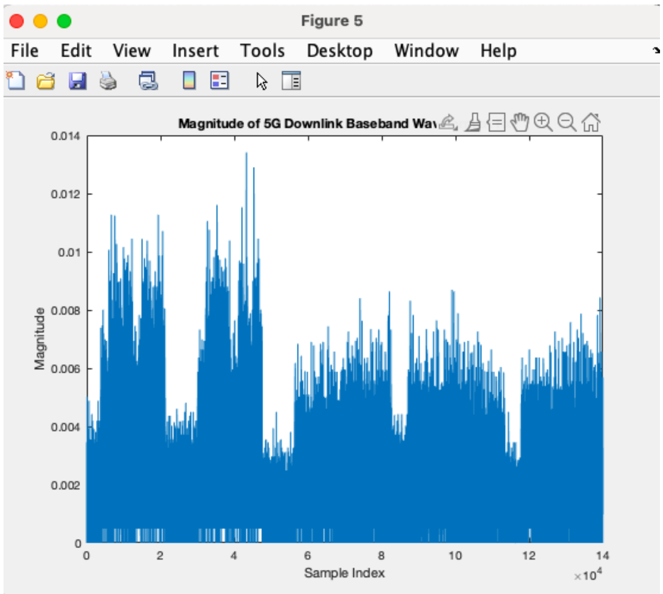
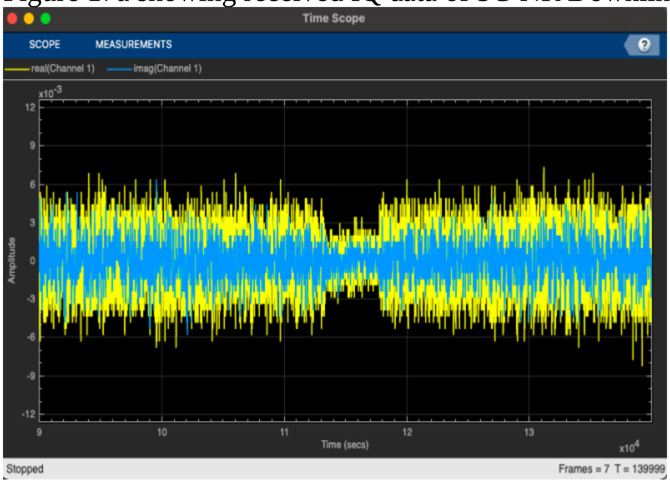


Figure 16b showing the Magnitude of 5G Downlink Baseband Waveform at Rx

The "Magnitude of 5G Downlink Baseband Waveform" in Figure 16a plot represents the absolute values of the generated baseband signal samples in the time domain before transmission. The generated baseband waveform contains all transmitted PDSCH, PDCCH, PBCH, PSS, SSS, and CSI-RS, along with their associated DM-RS and PT-RS. The signals are added together in the time domain, which leads to the peaks and valleys observed in the magnitude plot. These variations show the constructive and destructive interference that happens when multiple signals overlap.

The "Magnitude of 5G Downlink Baseband Waveform" Figure 16a and "Magnitude of 5G Downlink Baseband Waveform at Rx" Figure 16b plot have obvious differences. There seems to be smearing observed in this too as in the Tx plot, there are seen spaces between sample. Index plot unlike the Rx. This is due to the impact of the transmission medium and the receiver's processing. During transmission, the wireless channel gives rise to impairments such as multipath fading, shadowing, propagation loss and Doppler shifts causing a difference between the received signal and transmitted signal. As seen from Figure 16b, the Rx side is affected by additive noise (such as thermal noise) and interference from other signals in the environment which caused distortions in the received signal's magnitude and shape.

Figure 17a showing received IQ data of 5G NR Downlink



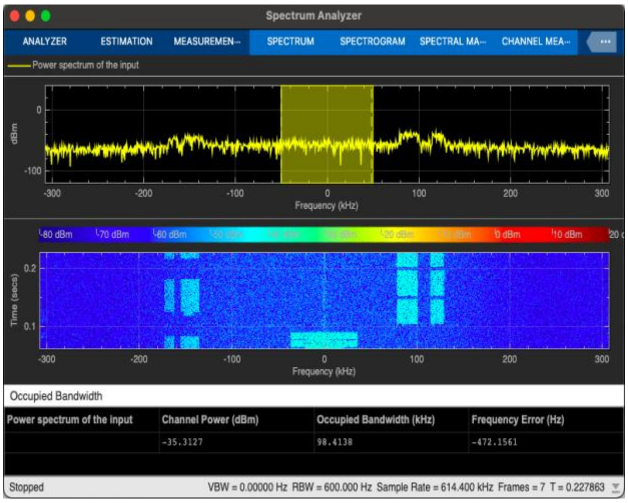


Figure 17b showing PSD and Spectrogram of 5G NR Downlink

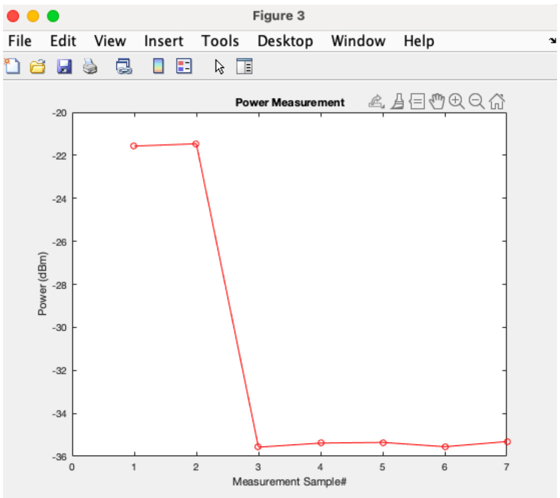


Figure 18 showing received power of received sine wave tone

The Channel power in dBm is -35.3127, the occupied bandwidth is 98.4138 kHz in which most of the frequencies of the signal's power is concentrated. The Frequency error is -472.1561 Hz.

Power measurement graph in Figure 18 shows peaking at 21.5 dB at sample 1 and a drastic drop to about -35.4 dB at sample 3: This observation suggests that the power of the received signal varies significantly over time. The high peak at the first measurement sample is due to the presence of a strong signal component and the drop in power indicates the presence of weaker signal components, such as data channels or the lower-power reference signals.

Task 4

5G New Radio (NR) use cases are grouped into three:

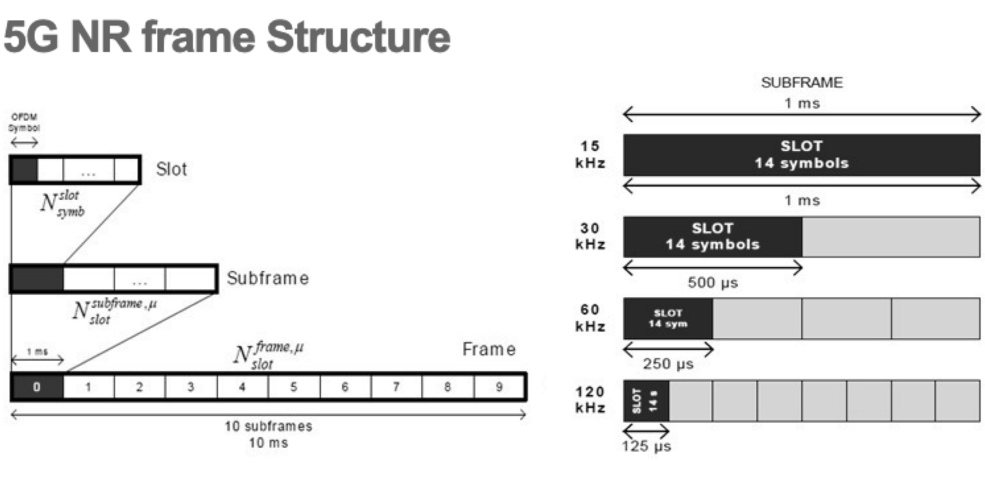
1. Enhanced Mobile Broadband (eMBB) which is a use case that provides higher data rates, lower latencies, and improved capacity to support various applications such as high-definition video streaming, virtual reality, and augmented reality.
2. Ultra-Reliable Low-Latency Communication (URLLC): This use case aims to provide highly reliable and low-latency communication for critical applications such as industrial automation, smart grid, and autonomous vehicles.
3. Massive Machine Type Communication (mMTC): This use case is designed to support many low-power devices with low data rates, such as IoT devices and sensors and meters in a highly efficient manner. These devices don't cost a lot being below $5. They support devices that transmit small packets. [2]

PDSCH (Physical Downlink Shared Channel) is a channel that carries user data and is used for both eMBB and mMTC use cases. It is transmitted with DM-RS (Demodulation Reference Signals) and PT-RS (Phase Tracking Reference Signals) for channel estimation and phase tracking.
PDCCH (Physical Downlink Control Channel) channel carries control information such as resource allocation and scheduling decisions. It is also transmitted with associated DM-RS for channel estimation.
PBCH (Physical Broadcast Channel) channel carries system information necessary for the initial access procedure. It is transmitted with its associated DM-RS for channel estimation.
PSS (Primary Synchronization Signal) and SSS (Secondary Synchronization Signal) signals are used for cell search and synchronization. PSS is used for symbol timing and cell ID detection, while SSS is used for frame timing and cell ID disambiguation.
CSI-RS (Channel State Information Reference Signal) signals are used to estimate the channel state and to support beamforming, beam management, and link adaptation.

NR Non-Standalone (NSA) mode refers to the deployment of 5G NR with 4G LTE network. In this mode, the 5G NR network relies on the LTE network for control plane operations and initial access, while the data plane is handled by the 5G NR network. This allows for a smoother transition to 5G and enables operators to leverage their existing LTE infrastructure. [3]

5G frame structure numerology is defined by subcarrier spacing and the duration of the OFDM symbols. There are five numerologies (μ = 0, 1, 2, 3, 4) and they all correspond to their different subcarrier spacing: μ = 0: 15 kHz, μ = 1: 30 kHz, μ = 2: 60 kHz, μ = 3: 120 kHz and μ = 4: 240 kHz.
The 5G frame structure contains 10 ms frames, which are divided into 10 subframes of 1 ms each. Each subframe is further divided into slots, with the number of slots per subframe depending on the numerology used. The different numerologies enable 5G to support a wide range of use cases and deployment scenarios.
Each slot consists of 14 OFDM symbols that carry the data and control information on the subcarriers. The 5G NR frame is divided into two equal-sized half-frames, with 5 subframes each. Half-frame 0 contains subframes 0 to 4, and half-frame 1 has subframes 5 to 9. [4]

The sketch to demonstrate this is shown below in Figure 19



[4]

In the physical layer, these signals and channels are transmitted using OFDM modulation. The OFDM waveform has multiple subcarriers, spaced closely together but orthogonally to each other to avoid interference. The signals and channels are mapped onto these subcarriers and transmitted over the air interface.
At the receiver side, the transmitted waveform is processed to extract the relevant channels and signals. Channel estimation and equalization are performed using the reference signals (DM-RS, PT-RS, and CSI-RS) to recover the transmitted data and control information. The PSS and SSS are used to get synchronization and cell identification, which are needed for establishing a connection with the network.

Task 5

Initial access in 5G is the procedure that enables a user equipment to establish a connection with the network. Processes such as cell search, synchronization, and random-access procedures. The user equipment detects synchronization signals (PSS/SSS), then gets system information from PBCH, and then performs a random-access procedure using PRACH.

In 5G, mmWave frequencies are used to achieve higher data rates, but these signals have higher path loss and are more susceptible to blockage. Beamforming overcomes these issues by focusing the radio energy in a specific direction, forming beams. Beam management in 5G involves beam sweeping, measurement, and tracking to maintain a high-quality link between the user equipment and the base station (gNB). [5] [7]

BWPs are introduced in 5G-NR to manage frequency resources better. Some use cases for BWP are:

1. Supporting devices with different bandwidth capabilities within the same carrier.
2. Efficient power consumption by adapting to user equipment's traffic demands.
3. Improving link adaptation by applying different subcarrier spacings for control and data channels.

LTE and 5G-NR Physical Layer Differences

Feature	**LTE**	**5G-NR**
Modulation	QPSK, 16QAM, 64QAM, 256QAM	QPSK, 16QAM, 64QAM, 256QAM, 1024QAM
Frame Structure	Subframes (1ms), 15kHz subcarrier spacing	Flexible numerology with subcarrier spacing of 15, 30, 60, 120, or 240 kHz, and slots of varying length
Frequency Bands	Up to 6 GHz	Up to 100 GHz, including mmWave frequencies
Carrier Bandwidth	Up to 20 MHz	Up to 400 MHz (FR1), Up to 800 MHz (FR2)
MIMO and Beamforming	Limited MIMO support, no beamforming	Advanced MIMO support, beamforming essential for mmWave frequencies
Access Technology	OFDMA (DL), SC-FDMA (UL)	OFDMA (DL), DFTs, OFDM (UL)
Channel Sounding	CSI-RS and SRS	CSI-RS, SRS, and TRS

[5]

Conclusion

After analysing the spectral characteristics and 5G-NR uplink/downlink waveform analysis with PlutoSDR, I gained valuable insights into the operation and behaviour of modern 5G wireless communication systems. The report shows the effectiveness of PlutoSDR in analysing and interpreting uplink and downlink waveforms and highlighting its versatility. The results gained mostly showed the differences between Tx (transmission) and Rx (Receiving) waveforms.

References

[1] Lodro, M. (2021) ‘Spectral Analysis and 5G-NR Uplink/Downlink Waveform Analysis Using PlutoSDR.’ Nottingham: George Green Institute for Electromagnetic Research-GGIEMR University of Nottingham, UK.

[2] 5G / New Radio use cases (no date) 5G / New Radio Use Cases and Requirements. Available at: http://anisimoff.org/eng/5g/5g_uc_requirements.html (Accessed: 10 May 2023).

[3] 5G NR (2023) Wikipedia. Available at: https://en.wikipedia.org/wiki/5G_NR#:~:text=The%20non%2Dstandalone%20(NSA),focused%20on%20the%20user%20plane. (Accessed: 10 May 2023).

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[5] Ahmed, S. (2019) ‘BEAMFORMING MANAGEMENT AND BEAM TRAINING IN 5G SYSTEM’. Faculty of Information Technology and Communication Science Tampere University.

[6] *5G* (no date) *ShareTechnote*. Available at: https://www.sharetechnote.com/html/5G/5G_CarrrierBandwidthPart.html (Accessed: 10 May 2023).

[7] *RF Wireless World* (no date a) *5G NR Initial Access Procedure | 5G NR Random Access Procedure*. Available at: https://www.rfwireless-world.com/5G/5G-NR-Initial-Access-Procedure.html (Accessed: 10 May 2023).