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Executive Summary of the Thesis

Synthetic Aperture Radar Imaging using 5G NR Signals

Laurea Magistrale in Space Engineering – Ingegneria Spaziale

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Academic year: 2022-2023

Abstract

This dissertation aims to explore the detection of synthetic aperture radar (SAR) using new 5G radio (NR) signals within the Joint Communication and Sensing (JCAS) framework. Integration of communication and sensing, JCAS, has garnered interest in recent years. The thesis focuses on the use of telecommunication signals for simultaneous sensing and transmission of communication. It investigates the generation of 5G NR signals, examining various configurations and range compression schemes. The analysis delves into the impact of physical channels and signals on range compression. MATLAB simulations assess the sensing capabilities of 5G signals, comparing the impulse response function with a chirp. High-resolution automotive data is manipulated to emulate 5G NR SAR, and Inverse Synthetic Aperture Radar (ISAR) is applied to compute the trajectory of a dynamic target. The study concludes with promising results, indicating the potential for conducting actual SAR experiments using 5G NR signals, especially in mmWave communication.

1. Introduction

The future landscape of advanced applications envisions wireless networks beyond 5G and 6G as promising solutions, requiring high-quality sensing and communication capabilities. Commonalities between communication and sensing, such as algorithms and system architecture, arise due to improvements in frequency bands and antenna arrays. The fusion of communication and sensing, driven by ample bandwidth opportunities in 3GPP release 16.2.0 for 5G NR, has become a focal point of research. Coexistence, cooperation, and joint design in Communication and Sensing ($C\&S$) systems are explored, with a focus on interference management during simultaneous operation. This unification opens the potential for wireless systems to offer ubiquitous sensing services, enhancing applications such as remote sensing, environmental monitoring, vehicle-to-everything, smart home, human-computer interaction, and smart manufacturing.

2. Characterization of transmitted signal

In the fast upgrading wireless communication network, fifth generation networks has emerged as life changing paradigm that revolutionized digital world in terms of how we communicate and interact. This revolution has been witnessed in reality with the sophisticated and ver-

satile modulation scheme known as Orthogonal Frequency division Multiplexing (OFDM). The success of the New radio flourishes because of OFDM scheme which promises very high data rates, excellent optimization of wireless spectrum, and mitigation techniques formulated for interference management.
The radar sensing is performed in a 5G network utilizing the known waveform with a frequency domain radar processing to detect targets or image the surroundings. 5G NR provides a variety of configuration setups of the resource grid in both uplink and downlink waveform generation. The radar data processing detects the delay using the known frequency domain symbols in the OFDM resource grid. A 5G NR waveform is generated that respects all 3GPP standards, including all logical channels, physical channels, and signals in an OFDM resource grid. A resource grid is a matrix of size $A \times B$, where A is the number of sub-carriers [Frequency] and B is the number of OFDM symbols [Time].

2.1. Resource Grid Configuration

To start with the generation of transmit waveforms, the 5G resource grid should be configured in compliance with 3GPP standards. There are several configurations implemented in this thesis. One of the specification is displayed in Table 1.

Parameter	Value
Numerology	3
Δf	120e3
Bandwidth	400 MHz
Nscs/slot	12
N_{sym}	14
N_{scs}	3096
N_{tot}	840
T_{frame}	10 ms
T_{slot}	0.125 ms
T_{sym}	8.9286e-6

Table 1: Resource Grid Config., FR2

All the parameters of carrier and bandwidth parts are defined before generating the OFDM grid. These parameters include frequency range, bandwidth, number of sub-frames, sub-carrier spacing, number of resource blocks not existing than maximum for the specified bandwidth, number of bandwidth parts, starting grid for sub-carrier spacing and bandwidth parts, type of cyclic prefix to fix the number of symbols in one slot, number of sub-frames, time duration for slots and symbol. Two configurations were tested to compare their performance for synthetic aperture radar. An empty OFDM resource grid was then generated using random integers and QPSK modulation, following specified sub-carrier and OFDM symbol sizes.

2.1.1 Physical Channel Configuration

The initially generated empty OFDM grid is populated with physical channels and reference signals, following 3GPP standards. When simulating a user transmitting and receiving a 5G signal for radar sensing, uplink channels (PUSCH, PUCCH) and reference signals (SRS) are incorporated into the OFDM resource grid. Three distinct configurations are employed to evaluate range compression performance, specifically focusing on the impact of modulation schemes in this context. One of the configuration is displayed in Table 2.

2.1.2 Configuration I

In the first configuration, the physical uplink shared channel, the physical uplink control channel and sounding reference signal are embedded. In this configuration, PUSCH uses 16 QAM modulation scheme, whereas PUCCH and SRS are QPSK modulated. All the other setups for each channel have been inserted in the table below.

Channel/Signal	Modulation scheme	Configuration
PUSCH	16 QAM	Mapping Type - B Start Symbol - 5 Symbol Length - 6 Period - 8 PRB - 210
PUCCH	QPSK	Format - 2 Start Symbol - 1 Symbol length - 4 Period - 10 PRB - 150
SRS	QPSK	K_{TC} - 2 Start Symbol - 13 Symbol Length - 2 Period - 12 PRB - 7

Table 2: Channel specification for Configuration I

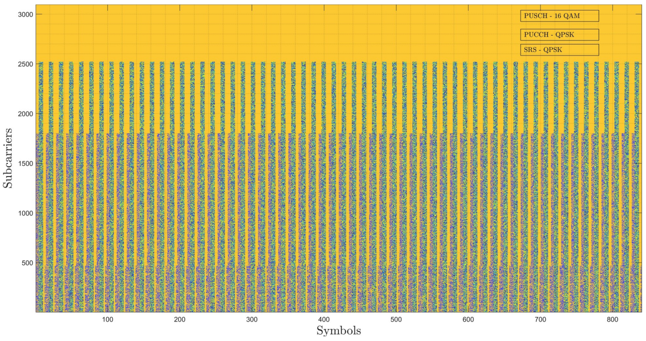

Figure 1: Resource Grid Configuration I

3. Transmit Waveform Generation

The 5G NR waveform format, based on CP-OFDM, shapes the physical structure of signals transmitting modulated symbols through a channel. This format is defined by core components: symbol, pulse form, and grid. Symbols, comprising complex numbers formed from combined bits, determine the modulation order. The signal matrix, aggregated with sub-carriers, undergoes shaping using filters like rectpuls, sine, or cosine waves to limit energy spread across the spectrum. The grid, defined by sampling in time and frequency domains, dictates symbol space, with its shape influenced by the number of domains.

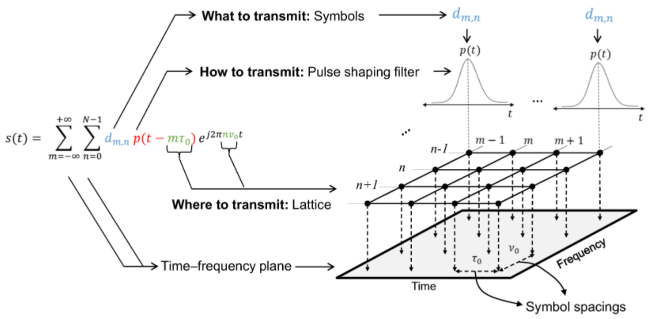

Figure 2: Waveform Structure Definition [1]

Figure2 from [1] is only for the representation for procedure of signal generation To modulate the OFDM resource grid R_G for creating a transmit pulse matrix with a designated OFDM symbol, symbols in the grid are converted to time domain samples. This involves constructing a time axis and a frequency axis based on the symbol duration and the number of sub-carriers, respectively.

$$M_{mod} = e^{(i2\pi t_{ofdm} \Delta f I)} \tag{1}$$

- t_{ofdm} → time axis of the OFDM signal
- I → axis of sub-carrier index
- Δf → Sub-carrier spacing

The OFDM resource grid is multiplied by the Fourier matrix to yield time-domain OFDM symbols. This matrix, sized $X \times Z$ (X: points in the time domain, Z: number of OFDM symbols), is then Hadamard multiplied with a pulse shaping filter, often a rectangular pulse of symbol duration, to constrain the transmit signal within the bandwidth.

$$s_{tx}(t) = \sum_{n=0}^{N} S(n) \cdot M_{mod} \cdot g(t) \tag{2}$$

- $S(n)$ → OFDM symbol
- $g(t)$ → Windowing function

Now, we have a transmit signal in the base band which should be up converted with a carrier to the pass band.

3.0.1 Frequency spectrum of transmit signal

In 5G, numerology involves optimizing numerical identifiers like frequency bands and network codes to enhance communication efficiency and connectivity in wireless networks. There are several numerology available in 5G NR which has variable frequency spectrum. We have attempted with few of them. But, for representation purpose we have put one of them. The bandwidth of the 5G signal has been analyzed for both the frequency range of NR. The figures 3 represent the transmit signal with bandwidth of 50 MHz for frequency range 1 and a bandwidth of 400 MHz for frequency range 2.

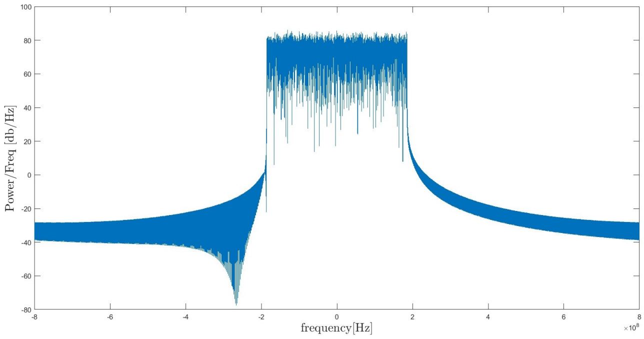

Figure 3: Frequency Spectrum of 5G OFDM Signal in FR2

4. OFDM Radar - Signal Processing

In OFDM radar processing, the transmit signal interacts with the targets, and the reflections are demodulated and Fourier transformed to regenerate the OFDM grid. Distance and velocity in radar data processing are related to delay and Doppler shift. Phase shifts caused by propagation delay are exploited for target range estimation, while Doppler shift-induced phase shifts are used for velocity computation. Various methods, including matched filtering or range compression, are employed to estimate these phase shifts in radar data processing. Three signal processing schemes were explored in this thesis.

1. Time domain Cross Correlation
2. Frequency domain Cross correlation
3. Equalization

4.0.1 Time Domain Cross-Correlation

In time domain, cross correlation is simply a convolution of received signal with transmit signal but time reversed and complex conjugated [3]. The output is a cross-correlation waveform whose peak indicates the corresponding time delay of for different targets. This approach improves radar imaging to discriminate closely spaced objects and offering very fine details in the resulting image.

$$\mathrm{g}(t) = s_{rx}(t) * s^*_{tx}(-t) \tag{3}$$

where,

s_{tx} → transmitted waveform

s_{rx} → received waveform

Different types of modulation schemes has been used for various channels and signals in alternate configurations in order to analyse the peaks of the cross correlation of the generated signal. These modulation schemes include BPSK, QPSK, 16 QAM, 64 QAM and 256 QAM. The range compressed signal has been plot for each modulation scheme and zoomed version of the same. The following figure depicts various range compression schemes.

4.0.2 Frequency domain Cross-Correlation

Frequency domain cross-correlation simplifies signal processing by multiplying the received signal with the complex conjugate of the transmit signal. This method, more efficient than its time domain counterpart, utilizes Fourier transform for range resolution, reducing hardware complexity. It is robust in noisy environments, less prone to phase errors, and particularly effective for analyzing complex waveform spectral characteristics.

$$\mathrm{G}(f) = S_{rx}(f)S^*_{tx}(f) \tag{4}$$

where,

S_{tx} → transmitted signal in frequency domain

S_{rx} → received signal in frequency domain

$G(f)$ → cross correlated signal in frequency domain

The range compressed signal is converted back into time domain using an inverse Fourier transform as follows,

$$s_{tx}(t) = IDFT(G(f)) \tag{5}$$

4.0.3 Equalization or channel estimation like scheme

Alternatively, there is another method to estimate the delay, which is a channel-estimation like scheme called Equalization. In frequency domain, equalization is just a element wise division of received signal by transmitted signal. The equalized signal is then converted in time domain to compute the delay.

$$G_{eq}(f) = \frac{S_{rx}(f)}{S_{tx}(f)} \tag{6}$$

where,

S_{tx} → transmitted waveform in frequency domain

S_{rx} → received waveform in frequency domain

5. Comparison of different modulation scheme and range compression scheme

Different modulation schemes (QPSK, 16 QAM, 64 QAM, BPSK) are assigned to specific channels in three configurations. The correlation peaks for transmit signals on various resource grids were examined, focusing on range compression schemes with simple delays and no signal noise. All modulation schemes exhibit sharp peaks, which improves precise delay extraction. For phase-shift keying and quadrature amplitude modulation, modulation order impacts phase variation tracking in the presence of noise and interference. To visualize peaks, frequency domain processing and equalization are compared for 16 QAM , and the error between them is plotted in figure 5.

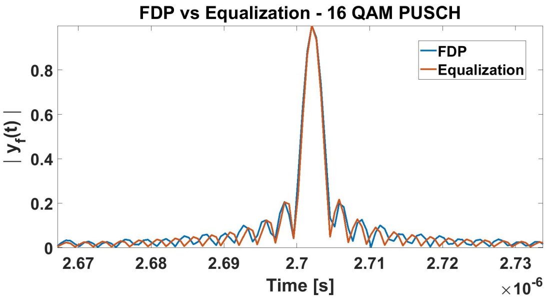

Figure 4: FDP and Equalization-16QAM

For visualization only one modulation scheme has been displayed. The Figure 4 shows the delay peaks with frequency domain processing and equalization when modulated using 16 QAM,

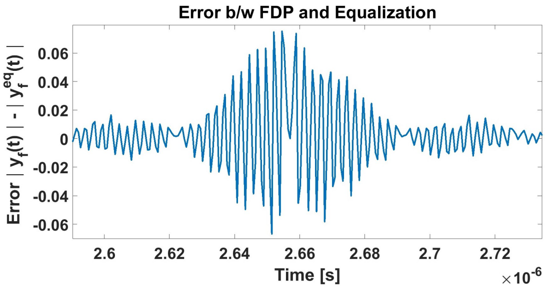

Figure 5: Error between FDP and Equalization (16QAM)

QPSK and BPSK, with fewer phase states, yield more efficient and precise value determination due to their distinct phase transitions. BPSK's inherently binary correlation peaks simplify cross-correlation, ideal for cases requiring a binary outcome.

6. Simulation of SAR system using 5G waveform on point targets

MATLAB is used for numerical simulations, validating the processing method before testing 5G NR with real data and SAR images. This ensures that the readers can compare the presented ideal results with forthcoming real results for enhanced clarity.

6.0.1 SAR Parametrization

Thus, a SAR system working in sub-6GHz has been designed. A small scene has been designed to mimic the real experiment with automotive data that will be analyzed later. Thus, a scene with maximum range of 30 meters has been created in a 2D space. The parameters of SAR system are tabulated in table 3,

Notation	Parameter	Value
f_0	Frequency	3.5 GHz
B	Bandwidth	1GHz
λ	Wavelength	8.57 cm
ρ_r	Range Resolution	15 cm
ρ_{az}	Azimuth Resolution	15 cm
L_x	Antenna Length along x	30 cm
Δ_ψ	Azimuth Bandwidth	0.2857

Table 3: Radar Parameters

6.0.2 Simulated Scene

The scene has been simulated similar to a automotive case with considerably long synthetic aperture because of sub-6GHz frequency range. Some of the important parameters computed for the synthetic aperture are tabulated below,

Notation	Parameter	Value
r_{min}	Minimum Range	5 m
r_{max}	Maximum Range	30 m
A_s	Synthetic Aperture Length	8.57 m
PRI	Pulse Repetition Interval	8.93 μs
PRF	Pulse Repetition Frequency	112 KHz
dx_{ant}	Spatial sampling step	0.0214 m

Table 4: Parameters of the scene and signal

With all the mentioned parameters, a 2D scene has been generated with 3 targets. Figure 6 helps to visualize the scene,

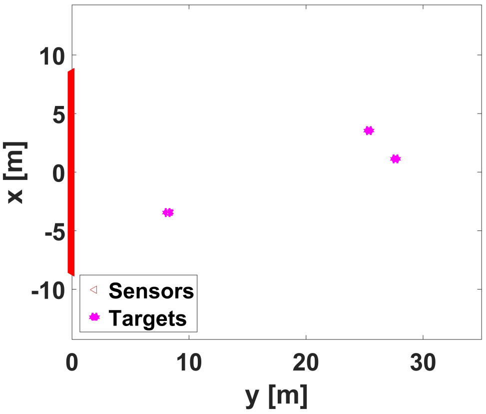

Figure 6: Simulated Scene with point targets

6.0.3 Simulating acquisition after range compression

Range compression, crucial for high-resolution radar images, aligns received data with target distances. Computed minimum and maximum delays initialize compression, determining the range axis. The process involves calculating distances, generating cardinal sine waves with range and phase terms, and summing signals for all targets, stored in the matrix [4]. This code exemplifies range compression's pivotal role in improving radar imagery precision and spatial representation of objects. All the range compressed signals generated for each sensor position(slow time) have been arranged in a sequence, to generate the range compressed data. This data could be visualized as an image better as follows,

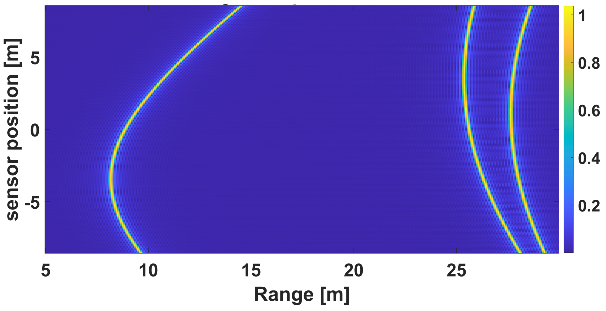

Figure 7: Range Compressed Data

6.0.4 5G NR SAR emulator

To simulate a 5G SAR system, the 5G NR waveform is convolved with range compressed data from point targets, following insights from [2]. Subsequently, the convolved signal undergoes further range compression with the 5G signal for data processing in the focusing algorithm [3]. Both time and frequency domain processes are applied.

6.0.5 Time Domain Processing

Following the associative property of signal theory, the proposed step was done by performing an auto-correlation of the transmitted signal and making a convolution of the auto-correlation with the range compressed data of the SAR system. The process is done as follows,

$$\mathrm{A_c}(t) = S_{tx}(t) * S_{tx}^{*}(-t) \tag{7}$$

where,

$S_{tx} \rightarrow$ transmitted waveform

$A_c \rightarrow$ Auto-correlation of the 5G NR signal

After the convolution, the auto-correlation of the 5G NR signal is convolved with the range compressed data as following,

$$\mathrm{G_{NR}}(t) = G_{chirp}(t) * A_c(t) \tag{8}$$

The three peaks of three point targets could be seen from the signal after range compression,

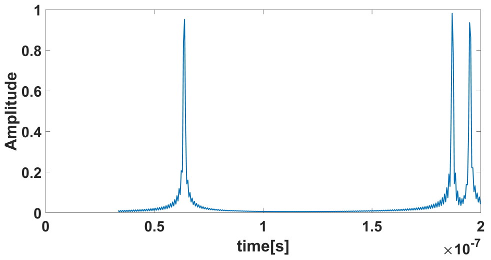

Figure 8: Range Compressed signal before convolution with 5G NR

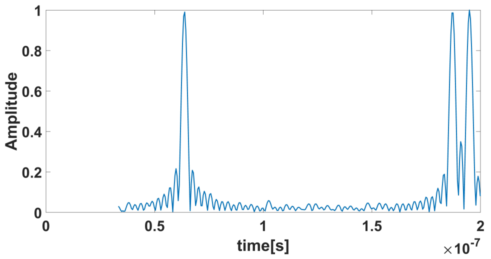

Figure 9: Range Compressed signal after convolution with 5G NR

Its very essential to analyse the peak of the targets in signals after range compression. Since, the bandwidth of two signals are different, the convolution between them makes the system bandwidth to the one which is least of the two. Hence, the width of the peak has been enlarged corresponding to the bandwidth of the 5G NR signal, which is 400 MHz.

6.0.6 Time domain Back projection

After simulating the 5G SAR, a time domain back projection algorithm focuses the image on a 2D grid. The new range grid is computed by finding distances from each grid point to sensor positions, and the range compressed data is interpolated, summed for all sensor positions to obtain the impulse response function.

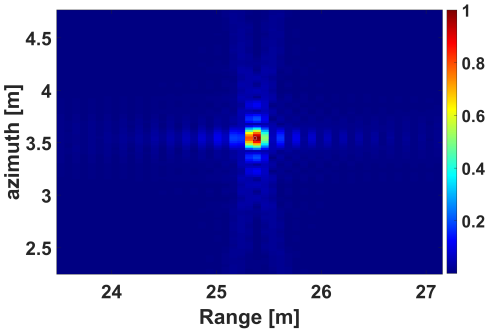

Figure 10: Focused SAR image - Zoomed

The Figure 10 is the zoomed image of the point target before convolving with OFDM signal, which has same range and azimuth resolution.

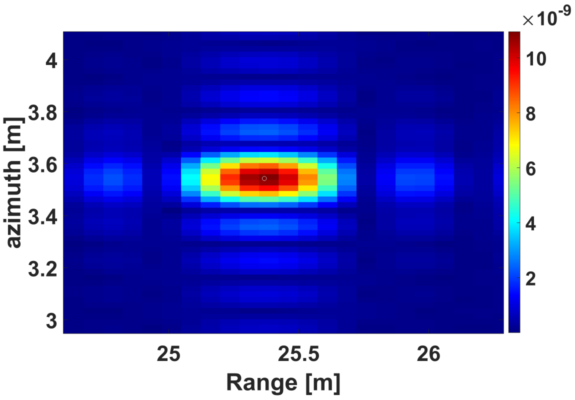

Figure 11: Focused SAR image with OFDM convolved-zoomed

The Figure 11 is the zoomed image of the point target after convolving with OFDM signal, where we see increased resolution because of lower bandwidth of the 5G NR signal.

7. 5G SAR emulation with Automotive data

To validate the MATLAB simulation, the same processing technique was applied to real automotive data acquired from an 8-channel MIMO radar operating at 77GHz during an open road campaign. The data includes side-looking SAR, forward SAR, and SAR imaging of moving targets. The MIMO array, is mounted on a car (ego-vehicle) to observe the scene, assuming pulse transmission at a pulse repetition frequency (PRF). A small portion of the data is striped from a very big data acquired from on road campaign. The data taken for OFDM processing is around 36.7 ms, to assess the performance of 5G NR signal.

Notation	Parameter	Value
B	Bandwidth	1GHz
f_0	Frequency	77GHz
PRF	Pulse Repetition Frequency	7 KHz
PRI	Pulse Repetition Interval	14.286ms
ρ_r	Range Resolution	15 cm
v	Vehicle Velocity	$\simeq 25\ \frac{km}{hr}$
dx_{ant}	Spatial sampling step	97.335 mm

Table 5: Automotive SAR parameters

7.1. Raw range compressed Automotive data

The three-dimensional data ($512 \times 256 \times 8$) consist of 512 samples in fast time, 256 samples in slow time, and 8 channels in MIMO radar. To visualize the range compressed data, computing the incoherent mean along the 3rd dimension (channels) is essential.

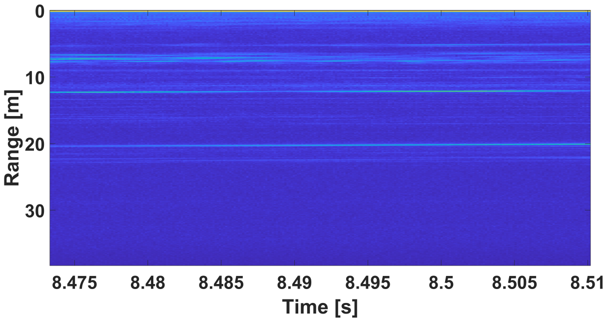

Figure 12: Incoherent mean of the range compressed automotive data

7.2. 5G OFDM Automotive SAR emulator

To mimic 5G OFDM Automotive SAR, a modified 5G waveform is generated based on the simulation with point targets, adjusting specifications like the number of frames and sampling time. Refer to Table 6 for signal details during further processing.

Parameter	Value
Numerology	3
Δf	120e3
Bandwidth	400 MHz
Nscs/slot	12
N_{sym}	14
N_{scs}	3096
N_{tot}	280
T_{frame}	10 ms
T_{slot}	0.125 ms
T_{sym}	8.9286 μ s

Table 6: OFDM Resource Grid Setup

For SAR system simulation with a 5G NR waveform, the generated 5G NR waveform is convolved with range compressed data from point targets, simulating a 5G SAR system. This convolved signal undergoes further range compression with the 5G signal for data processing in both time and frequency domains.

7.2.1 Time Domain Processing

For Automotive SAR simulation with a 5G NR waveform, the generated waveform is convolved with range-compressed urban scenario data, emulating a 5G SAR system. Subsequently, the convolved signal undergoes another range compression with the 5G signal within the focusing algorithm, performed in both time and frequency domains. To initiate, the auto-correlation of the 5G NR waveform is computed and convolved with the range-compressed automotive signal, followed by convolving the OFDM signal with data from all 8 MIMO radar channels.

$$\mathrm{A_c}(t) = S_{tx}(t) * S^*_{tx}(-t) \tag{9}$$

where,

S_{tx} → transmitted waveform

A_c → Auto-correlation of the 5G NR signal

The time domain processing mentioned here is implemented on real automotive data in a similar way as shown in section 4

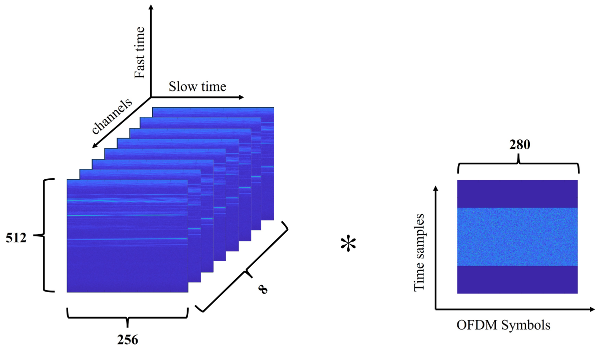

Figure 13: Convolution of Range compressed automotive data with 5G NR signal

After the convolution, the auto-correlation of the 5G NR signal is convolved with the range compressed automotive data through all the 8 channels as following,

$$\mathrm{G_{NR}}(t) = G_{automotive}(t) * A_c(t) \tag{10}$$

Here, $G_{automotive}$ is a 3-dimensional data, therefore, we repeat the equation 10 for all the 8 channels as shown in figure 13 Demonstrating the 5G NR signal's ability to reproduce original range compressed data with significantly lower bandwidth, plots of the incoherent mean for one range compressed signal across all channels are presented.

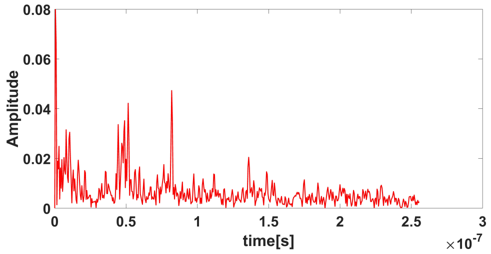

Figure 14: Range compressed automotive data signal before Convolution

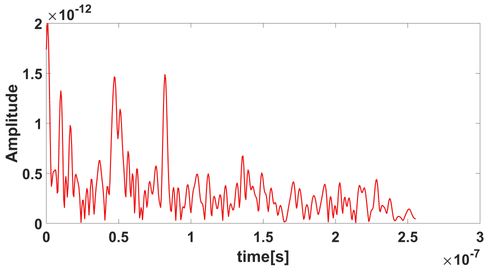

Figure 15: Range compressed automotive data signal after Convolution

7.3. SAR Focusing

The convolved data is back-projected using a fast time domain algorithm after undergoing calibration for static and dynamic range correction, including phase and time offset adjustments, along with small corrections to x and y components of velocity. With these inputs, the range compressed data is focused on the proposed grid, reproducing SAR images.

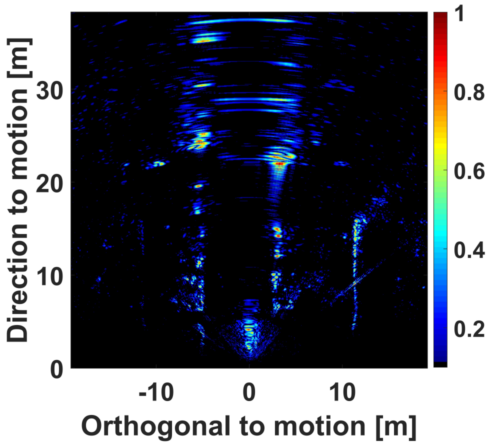

Figure 16: Real Automotive SAR image back-projected with TDBP

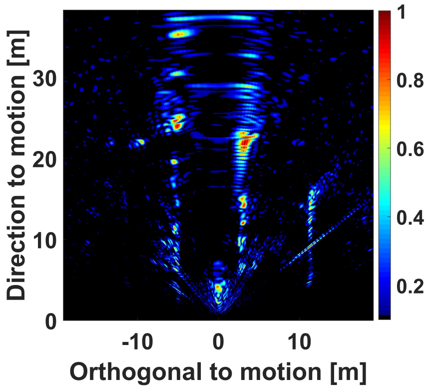

Figure 17: OFDM convolved Real Automotive SAR image processed in time domain

To have a better visualization of important peak of the plot, its essential to plot all three pictures together with their axes linked and zoom the areas of interest as follows,

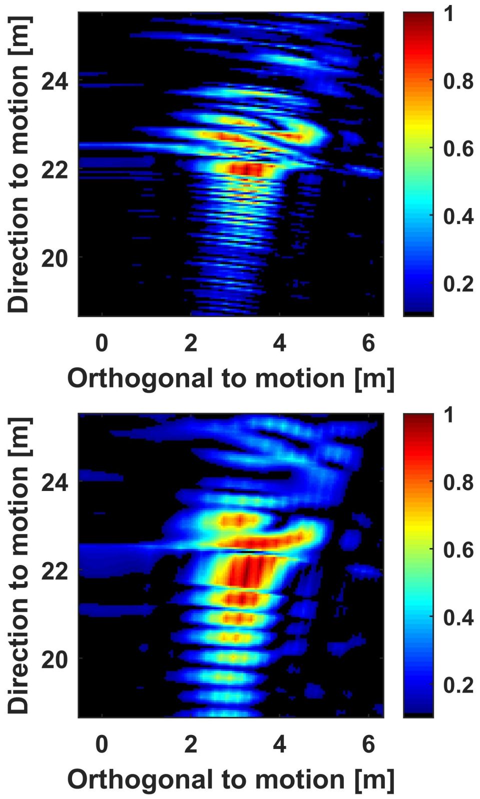

Figure 18: Comparison of three SAR images on specific spots

8. Inverse SAR application and 5G NR

Inverse Synthetic Aperture Radar (ISAR) involves capturing and processing radar reflections from a moving target. In this simulation, 5G waveform's performance in an ISAR application is assessed using automotive range compressed data containing a moving target (a lady on a bicycle). The goal is to compute the target's motion law, specifically the change in X and Y components over slow time, comparing the effectiveness of 5G NR waveform with chirp using the model. To visualize the moving target, phase derivatives are computed.

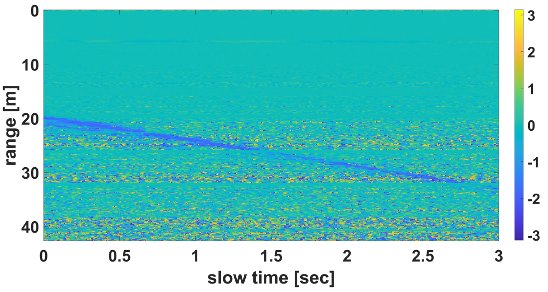

Figure 19: Phase derivative of range compressed automotive data

In Figure 19, we can see a blue line starting from range 20 meters and moving through slow time to around 30 meters. The goal of this simulation is to compute that trajectory by processing the radar data.

8.1. Methodology

In this simulation, a portion of the 3D data is selected for processing. A fast Fourier transform along the third dimension (channels) computes the angles of the targets, followed by another fast Fourier transform along the slow time direction to determine the velocity of the targets.

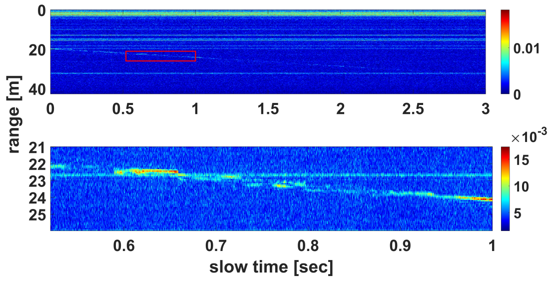

Figure 20: Range Compressed data and processed range compressed data

The 'Angle FFT' along channels and 'Doppler FFT' along the slow time direction are performed. The resulting data cube represents range, angle, and velocity, capturing both static and moving targets. To identify the moving target (the lady), the strategy involves checking non-zero velocities and computing the parameters for the law of motion. Refer to Figure 21 for an overview of the radar data processing with the sizes of the fast Fourier transforms in each step.

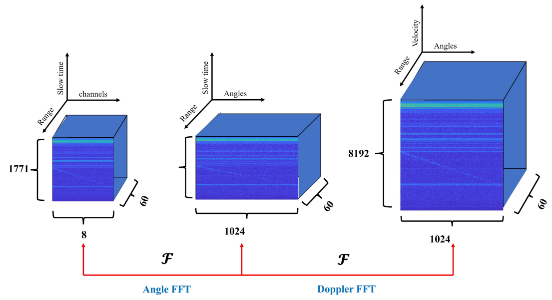

Figure 21: RADAR data processing

The velocities and angles are computed from doppler frequencies and spatial frequencies as follows,

$$V_{ax} = \frac{-\lambda}{2} * f_d \tag{11}$$

$$\phi_{ax} = \sin^{-1}\left(\frac{\lambda}{2} * f_{az}\right) \tag{12}$$

The range, velocity, and angle cube is visualized for nonzero velocities to identify peaks. Once a peak is found, the corresponding range and angle are extracted. An essential assumption is constant velocity, computed as the mean velocity from the data, indicating linear change in the lady's angle through the range.

Finally, once the range, velocity and angle are computed, the following equation for law of motion have used to compute the trajectory,

$$\begin{aligned} x(\tau) &= r \cdot \cos(\phi_{ax}) + v \cdot \tau \cdot \cos(\phi_{ax}) \\ y(\tau) &= r \cdot \sin(\phi_{ax}) + v \cdot \tau \cdot \sin(\phi_{ax}) \end{aligned} \tag{13}$$

Notation	**Parameter**	**Value**
r_{init}	Initial Range	21.0265 m
v_{mean}	Mean Velocity	4.1354 $\frac{m}{s}$
ϕ_{lady}	Angle of the lady	-4.3694 °

Table 7: Parameters to Compute Law of Motion

Thus, with these computed parameters and the equations 13, the trajectory can be computed. The Figure depicts the X and Y components of the moving lady,

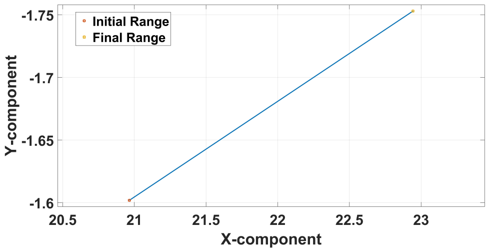

Figure 22: Law of Motion of target(lady) as a function of slow time computed using real range compressed data

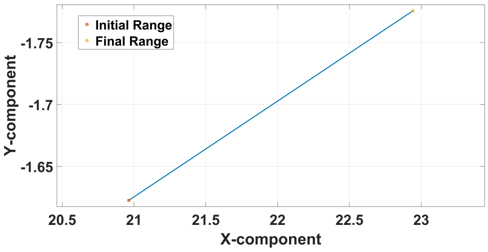

Figure 23: Law of Motion of target(lady) as a function of slow time computed using OFDM emulated range compressed data

The Figure 22 and 23 depicts the trajectory of the targets, which are quite identical. Hence, it is evident that the 5G NR waveform could able to retrieve the low of motion with a very good accuracy.
To witness the error imparted by OFDM, it is important to see the error in X and Y component.

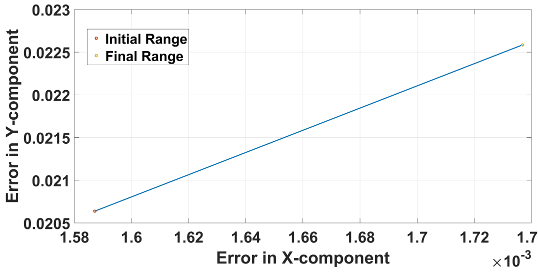

Figure 24: Error between real LOM and OFDM emulated LOM

An optical image of the real scene in Figure 25 has been attached below, to verify the ground truth of the target.

Figure 25: Optical Image of the range compressed data

9. Conclusion

In summary, this thesis explores the integration of 5G New Radio (5G NR) signals for Synthetic Aperture Radar (SAR) sensing, demonstrating the effectiveness of leveraging 5G NR waveforms for joint communication and sensing systems. The study highlights the viability of using 5G NR signals in SAR, enhancing radar sensing accuracy and efficiency by capitalizing on the waveform's versatility. The thesis focuses on studying 5G NR standards, testing various configurations, and assessing performance through simulations with point targets. Real data applications include reproducing SAR images using automotive radar and evaluating 5G NR's capabilities in an inverse SAR scenario, computing the law of motion for a moving target and assessing trajectory retrieval.

10. Bibliography

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