NATIONAL UNIVERSITY OF SCIENCE AND TECHNOLOGY POLITEHNICA BUCHAREST

Doctoral School of Electronics, Telecommunications and Information Technology

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Ph.D. THESIS SUMMARY

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CONTRIBUȚII ÎN DOMENIUL RADARULUI DE ÎNALTĂ REZOLUȚIE

CONTRIBUTIONS IN THE FIELD OF HIGH-RESOLUTION RADAR

THESIS COMMITTEE

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Chapter 1

Introduction

The FMCW (Frequency Modulated Continuous Wave) radar is a high-resolution radar representing essential advanced technology in the automotive field. This type of radar is designed to capture images or measurements with exceptionally high temporal and spatial precision, enabling clear distinction between objects at very close distances from one another. FMCW radar is characterized by its capability to detect and differentiate small-sized objects, such as pedestrians or road obstacles, even in challenging environmental conditions like rain, fog, or snow.

Another type of high-resolution radar is the Synthetic Aperture Radar (SAR), which stands out due to its unique ability to provide high-resolution 2D images regardless of lighting or weather conditions [35]. This capability makes it an extremely effective tool in fields such as remote sensing, geoscanning, mapping, environmental monitoring, and others. Spatial resolution is a critical performance metric of the SAR system, with higher resolutions offering more detailed information that facilitates target recognition, description, and extraction.

In the context of the expanding use of radar technologies across various fields, the emergence of interference presents a significant challenge that impacts radar performance in both the automotive sector and Synthetic Aperture Radar (SAR) systems. This scenario highlights the need for the development and implementation of advanced interference mitigation techniques to ensure optimal radar system operation in the face of challenges posed by electromagnetic spectrum congestion. In this thesis, we will examine the impact of interference on FMCW radars in the automotive industry and on SAR systems, present new interference suppression methods, and analyze current suppression techniques to identify interference elimination solutions that effectively address scenarios with different types of interference.

1.1 Presentation of the field of the doctoral thesis

The FMCW radar is widely used in the automotive industry within autonomous vehicles, forming the basis for driver assistance systems. This radar transmits chirp signals in a continuous wave with time-varying frequency, which are reflected by objects surrounding the vehicle. Due to its capability to measure distances and speeds with very high precision (on the order of centimeters), the FMCW radar is essential for functionalities such as adaptive cruise control, lane-keeping assistance, collision detection, and more. The high resolution of the FMCW radar has led to the development of applications where it is configured similarly to a SAR radar (i.e., mounted on an aerial platform) to obtain high-resolution 2D images comparable to those provided by a Synthetic Aperture Radar.[23].

The SAR is used for high-resolution imaging of large surface areas, making it essential in applications such as mapping, environmental monitoring, and terrestrial observation. The SAR operates by transmitting a radar signal and receiving its reflections while the radar is in motion, generating high-resolution images. Through aperture synthesis techniques, the SAR can produce detailed and precise images of terrestrial surfaces.

One of the major challenges in the operation of FMCW radar is the occurrence of mutual interference in heavy traffic scenarios where a high number of radars are present. Such interference can compromise radar system performance and impact vehicle safety. In the case of SAR, interference can affect image clarity and introduce errors in data analysis.

1.2 Scope of the doctoral thesis

The occurrence of radio-frequency interference in FMCW and Synthetic Aperture Radar (SAR) systems has become a topic of great interest due to the increased likelihood of such interference in typical scenarios. The primary objective of this doctoral thesis is to develop and evaluate efficient techniques for eliminating interference in FMCW radar used in the automotive industry and in Synthetic Aperture Radar. This includes identifying and implementing innovative methods that can enhance radar signal quality and the performance of detection and imaging systems. Specifically, the thesis aims to:

- Development of efficient interference mitigation methods:
    - Analysis and development of techniques that can reduce or mitigate interference from other radars in the automotive industry, where FMCW radar is widely used.
    - Analysis and development of interference mitigation methods for Synthetic Aperture Radar to improve image quality and facilitate accurate object identification.

- Study and analysis of interference - Investigation of interference types affecting FMCW and SAR radars, as well as analysis of the impact of various interference types on radar performance and identification of critical factors influencing signal quality.
- Development of synthetic databases simulating scenarios with mobile targets in the presence of interference, as well as experimental data acquisition to assess the effectiveness of interference mitigation methods in complex scenarios with different types of interference and a variable number of interference sources.
- Evaluation of the performance of proposed techniques:
  - Testing and comparing various interference mitigation methods under real and simulated conditions to determine their efficiency and impact on radar performance.
  - Conducting experiments and tests to validate the effectiveness of the proposed techniques in real and simulated conditions. Comparing the performance of proposed techniques with existing methods and assessing the impact on signal quality and processing time.
- Optimization of technique implementation in radar hardware:
  - Investigating how interference mitigation techniques can be efficiently integrated into existing radar hardware for FMCW radars in the automotive industry.
  - Assessing the impact on hardware and software resources and optimizing implementation to ensure compatibility and real-time performance.

By achieving these objectives, the thesis aims to make a significant contribution to improving radar performance in the context of interference mitigation, with a positive impact on detection and imaging applications. This will facilitate the development of more precise and reliable radar solutions, thus advancing radar technology and enhancing its applicability across various fields.

1.3 Content of the doctoral thesis

The structure of the doctoral thesis is divided into seven chapters, with each chapter presenting aspects related to radio frequency interference in high-resolution radars.

In **Chapter 1**, a brief introduction to high-resolution radars is provided, followed by an overview of the field, objectives, and content of the doctoral thesis.

In **Chapter 2**, the current state of research on interference in FMCW radar in the automotive industry and Synthetic Aperture Radar is presented. In **Chapter 3**, the theoretical, software, and hardware tools used in the doctoral thesis are presented.

In **Chapter 4**, the interference mitigation method using Short-Time Fourier Transform and Order Statistics (STFT and L-Statistics) is introduced. A series of simulations were conducted to analyze the method's performance in various scenarios, a comparison was made between the performance of the proposed method and other interference mitigation methods, and, at the end of the chapter, the real-time implementation of the method on the AWR1843 radar sensor is presented.

In **Chapter 5**, an interference mitigation technique based on polarization rotation is presented.

In **Chapter 6**, a new interference mitigation method for Synthetic Aperture Radar using a Filter Bank Time-Frequency Distribution and L-statistics is presented.

The thesis concludes with **Chapter 7**, a conclusion chapter where the most important results, personal contributions, list of published works, and future development perspectives are presented.

Chapter 2

Current State of Research

2.1 Current State of Research for FMCW Radar in the Automotive Industry

In the autonomous vehicle industry, radar sensors have become indispensable and play a crucial role in the development of applications such as Advanced Driver Assistance Systems (ADAS), Automatic Emergency Braking (AEB), Blind Spot Detection (BSD), Adaptive Cruise Control (ACC), and lane-changing assistance. To implement these applications, multiple radar sensors are required to be mounted on a single vehicle, all operating within the same frequency band (76-81 GHz). This setup leads to mutual interference among radar sensors that reduces the radar performance and becomes a critical issue from a safety perspective [27].

2.2 Classification of Interference Types in FMCW Radars

In the automotive industry, Frequency Modulated Continuous Wave (FMCW) radar is the most commonly used type. Given the increasing number of autonomous vehicles on the road and the fact that automotive radars operate within a narrow frequency band (76–81 GHz), there is a high probability that radar sensors will interfere with each other in heavy traffic conditions. Therefore, in a scenario where mutual interference is present, there is a victim radar (the radar receiving both the reflected signal from the target and the interference signal) and at least one interfering radar (the radar causing the interference) [5].

Depending on the specific parameters of the chirp sequences used by both the interfering radar and the victim radar, mutual interference can be classified as follows:

- Correlated or Parallel Interference
- Uncorrelated or Sweeping Interference

- Continuous Interference

2.3 Interference Suppression Methods

To address the problem of mutual interference among FMCW radars in the automotive industry, a range of algorithms have been developed for detecting and mitigating radio interference, either in the time domain [5], [9], the frequency domain [4], or the time-frequency domain [28]. Additionally, algorithms based on neural networks have been developed [21], [34], as well as algorithms that rely on waveform variation from one chirp to another [2]. However, it is worth noting that only a limited number of interference mitigation algorithms developed and tested on automotive radar transceivers are found in the specialized literature [30], [29].

In this thesis, I conducted a performance analysis of a set of five interference mitigation methods as follows:

- **Bi-Level L1 Optimization Method**
- **Zeroing Method**
- **Autoregressive Model Method**
- **Ramp Filtering Method**
- **Iterative Method with Adaptive Thresholding (IMAT)**

These methods were implemented in Matlab and tested on both simulated and real datasets for scenarios involving different types of interference.

2.4 Current State of Research for Synthetic Aperture Radar

The use of Synthetic Aperture Radar (SAR) enables data acquisition regardless of weather conditions and at any time. As such, it is widely used in applications such as disaster warning, environmental monitoring, mapping, natural resource management, and ocean monitoring. High-resolution imaging facilitates the use of SAR in the military domain, where it can be employed for identifying specific targets and monitoring the movement of troops and equipment on the battlefield. Additionally, SAR is valuable in detecting the locations of active sources operating within the same frequency band [24].

However, SAR functionality can be seriously compromised when active external sources, such as ground-based or airborne radar systems, telecommunications equipment, television networks, or even another SAR system, generate radio frequency interference. This interference phenomenon can significantly degrade the quality and accuracy of radar images, making data interpretation considerably more challenging and reducing the efficiency of the SAR system in target detection and analysis [25].

2.5 Methods for Radio Frequency Interference Mitigation in SAR

Various techniques have been designed to detect and mitigate the effects of interference in SAR images. Adaptive filtering methods have proven to be the most practical signal processing approach, characterized by their ability to design filters either in the frequency domain [20] or in the time-frequency domain [26].

Detecting interference in the time domain is quite challenging, especially when its level is similar to that of the echo from a target. However, by analyzing the interference-affected signal in the time-frequency domain, interference can be easily detected, as its bandwidth is narrower compared to that of the target's reflected echo signal.

In [14], an innovative method is presented that mitigates interference in three stages: Detection, Notch, and Recovery. In [13], [32], methods are proposed for suppressing interference between spaceborne SAR systems. Other innovative techniques propose interference mitigation [7] using alternating projections or tensor decomposition [11]. Additionally, other methods have been developed for locating interference and, thus, active radiation sources operating in the same frequency band as SAR [12], [1], [33].

In general, SAR interference mitigation methods are classified as follows:

- **Nonparametric Methods** -
- **Parametric Methods** -
- **Semiparametric Methods** -
- **Polarization-Based Methods**

Chapter 3

Theoretical, Software, and Hardware Tools Used in the Project

3.1 Description of the Operating Principle of FMCW Radar

Radar systems used in the automotive industry are generally Frequency Modulated Continuous Wave (FMCW) radars. These radars continuously transmit frequency-modulated signals to measure the distance, speed, and angle of arrival of a target.

The block diagram of an FMCW radar is illustrated in Figure 3.1, where the main radio frequency, analog, and digital components can be identified, helping to describe its operating principle.

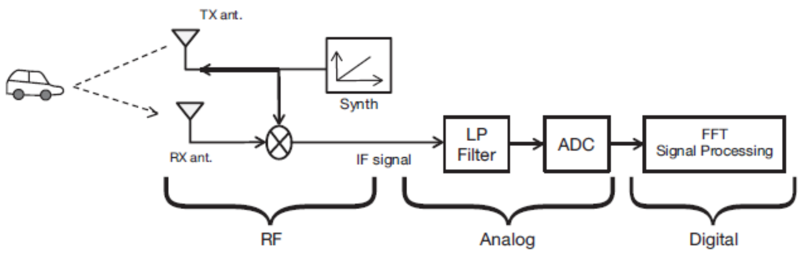


Fig. 3.1 Block Diagram of the FMCW Radar

A chirp signal is generated using a frequency synthesizer and transmitted via the transmission antenna (TXant). When this transmitted signal encounters an object, it reflects back, creating a reflected chirp signal that is captured by the receiving antenna (RXant). In the FMCW radar's receiving system, the transmitted chirp and the received chirp are combined using a mixer, forming an intermediate frequency (IF) signal or beat signal.

To obtain the time-frequency representation of the IF signal at the output of the frequency mixer, the difference between the slope of the TX chirp and the RX chirp is calculated. The IF signal is valid only during the time interval in which the TX chirp and RX chirp overlap [**?**].

3.2 Description of the Chirp Signal in the Presence of Interference

The signal transmitted by an FMCW radar, $s_T(t)$, within a repetition interval is a chirp signal with linear frequency variation:

$$s_T(t) = \cos\left[2\pi\left(f_c t + \frac{1}{2}k(t-T/2)^2\right)\right] p\left(\frac{t-\frac{T}{2}}{T}\right) \tag{3.1}$$

, where

$$p\left(\frac{t}{T}\right) = \begin{cases} 1, & \text{if } |t| \leq \frac{T}{2} \\ 0, & \text{if } |t| > \frac{T}{2} \end{cases} \tag{3.2}$$

is the rectangular function with duration T corresponding to a time interval, f_c is the carrier frequency, and k represents the slope of the transmitted chirp signal, equal to the ratio between the chirp signal bandwidth B and its duration T.

The transmitted signal is reflected by the target and received after a time delay τ_i, which is related to the radar-target distance $R_i = c\tau_i/2$ (where c is the speed of light in a vacuum). In the presence of interference, the signal received by the radar receiver will contain both the target-reflected signal and the signal transmitted by the interfering radar. Thus, the signal received by the radar receiver can be expressed as the sum of the signal reflected from the target and the signal transmitted by the interfering radar, as follows:

$$s_R(t) = \sum_{i=1}^{N_T} A_{R,i} s_T(t-\tau_i) + \sum_{l=1}^{N_{RFI}} s_{RFI,l}(t), \tag{3.3}$$

, where N_T represents the number of targets, $A_{R,i}$ represents the amplitude corresponding to target i, and N_{RFI} represents the number of interference sources.

After mixing the signal reflected from a point target with the transmitted signal, a constant frequency signal (the classic beat signal) is obtained, whereas mixing an uncorrelated interference with the transmitted chirp signal results in an interference chirp signal in the baseband.

The analytical expression of the resulting beat signal is written as:

$$
\begin{aligned}
x(t) = \Bigg\{ & \sum_{i=1}^{N_T} A_i \exp(j2\pi k\tau_i t) + \\
& + \sum_{l=1}^{N_{RFI}} A_{RFI,l} \exp\left[j\pi(k - k_{RFI,l})(t - t_{RFI,l})^2\right] \times \\
& \times p\left(\frac{t - t_{RFI,l}}{T_{AAF,l}}\right) \Bigg\} \times p\left(\frac{t - \frac{T}{2}}{T}\right),
\end{aligned} \tag{3.4}
$$

where A_i represents the complex amplitude of the target, and $A_{RFI,l}$ is the complex amplitude of the l-th interference signal. Therefore, the beat signal consists of a sum of complex exponentials with constant frequency (corresponding to the targets) and a sum of baseband chirp signals that describe the interferences.

3.3 Software and Hardware Tools Used in the Thesis

In developing interference mitigation methods, a suite of specialized software tools was used as follows:

- **MATLAB**
- **Code Composer Studio**
- **MMWaveStudio**
- **UniFlash**
- **LATEX**

3.3.1 Hardware Tools Used in the Project

The hardware devices used throughout the development of this doctoral thesis are as follows:

- **AWR1843 Radar Sensor** - The AWR1843 radar is an integrated single-chip FMCW sensor that operates in the 76-81 GHz frequency band.
- **DCA1000EVM** - This is a capture card designed to connect with the AWR1843 radar, providing users with the ability to transmit data from the analog-to-digital converter (ADC) via Ethernet.

Chapter 4

The Method Based on STFT and L Statistics for Interference Mitigation in FMCW Radar

In this chapter, an innovative method for mitigating uncorrelated interference in FMCW radar used in the automotive industry is presented. The method is based on Short-Time Fourier Transform (STFT) and L-Statistics and was proposed and published in [16].

Additionally, this chapter presents a comparison between the results obtained by applying the proposed method and other state-of-the-art methods, using both simulated and real datasets, for scenarios involving different types of interference. The chapter concludes with a presentation of the real-time implementation of the method.

4.1 Description of the Method

This section presents the algorithm developed for interference mitigation in FMCW radar, which is based on the analysis of radar signals in the time-frequency domain. The general diagram of the algorithm is shown in Figure 4.1.

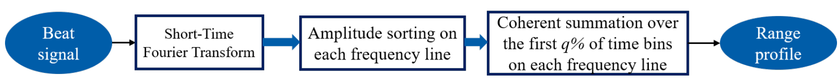


Fig. 4.1 Block diagram of the RFI mitigation algorithm based on STFT and L-statistics

The concept of the method involves computing the STFT of the beat signal and sorting each constant frequency line of the spectrogram in ascending order. This approach positions the bins affected by interference toward the higher end of the time-frequency plane. Subsequently, the interference-free range profile is calculated through coherent summation along the time axis of the bins deemed unaffected by interference (the first $q\%$ of the time bins in the sorted spectrogram).

4.2 Analysis of the Influence of Parameters Characterizing the Method

The range profile obtained after interference mitigation using the proposed method depends on the following parameters:

- Sliding window length N_{win} - which determines the temporal resolution and the width of the interference in the time-frequency plane.
- Step size of the sliding window N_{step} - which determines the computational time and the frequency resolution.
- Summation percentage q - which can be expressed as:

$$q[\%] = \left(1 - M_f \times \frac{N_{win}}{N_{STFT} N_{step}}\right) * 100, \tag{4.1}$$

  where M_f is a multiplication factor related to the number of interferences present in the signal.

4.3 Performance Evaluation of the Method

4.3.1 Evaluation on a Simulated Dataset

To evaluate the performance of the method in complex scenarios, the ARIM-v2 dataset, proposed in [22], was used. This dataset includes scenarios with multiple interference sources (ranging from one to three sources) as well as multiple targets (ranging from one to four targets). Using this dataset, the method's performance was analyzed for different parameter combinations in terms of the Mean Absolute Error (MAE) of target amplitudes and phases. It was observed that the best results were obtained when the multiplication factor was 3 or 4 and the sliding window length was $N_{win} = 32$ și $N_{win} = 64$.

4.3.2 Comparison of Range Profiles

Using the ARIM-V2 dataset, a comparison of range profiles was conducted, applying the proposed RFI mitigation method based on STFT and L-Statistics, the Zeroing method [10], [9], the "Fully Convolutional Network" (FCN) method based on neural networks [6], and Bi-Level L1 Optimization- Based Interference reduction method [31].

The comparison was performed using the Mean Absolute Error (MAE) of amplitude and phase based on the ARIM-V2 dataset. It was observed that the interference mitigation method based on Bi-Level L1 Optimization- Based achieves good performance for a single interference source but that the MAE increases when 2-3 interference sources are present, which degrades its overall performance. In contrast, the proposed method can effectively mitigate interference regardless of the number of interference sources.

In conclusion, the proposed method demonstrates superior performance compared to the other three methods, achieving the best results with the optimal parameter combinations identified through the simulations performed.

4.3.3 Comparison in the Range-Doppler Domain

To compare the effectiveness of the proposed method in scenarios involving moving targets with the effectiveness of the Zeroing method and the Bi-Level L1 Optimization-Based Interference reduction method, a dataset presented in [31] was used. This dataset captures a scenario in which a bicycle moves at a speed of 5 m/s while an interfering radar is strategically positioned 4 meters away from the victim radar.

It was observed that the moving target is clearly visible when the STFT and L-Statistics method and the Bi-Level L1 Optimization- Based are applied, while it is less visible when the Zeroing method is used.

Additionally, the estimation of distances and velocities of the target group was analyzed in the presence of short-duration interference (generated by an interference chirp with a slope equal to half the slope of the transmitted chirp, having a slope ratio of 0.5) and long-duration interference (generated by an interference chirp with a slope close to that of the transmitted chirp, having a slope ratio of 0.98). It was observed that all methods performed well for short-duration interference, whereas in the presence of long-duration interference, the proposed method effectively reduces the interference while keeping the targets visible.

4.3.4 Target Direction Estimation

To evaluate the accuracy of target direction estimation, a specific dataset presented in [31] was used. The data were acquired for a scenario where the angular positions of two targets, a car and a motorcycle, were determined.

For the dataset corresponding to the described scenario, the STFT and L-Statistics method, the Zeroing method, and the Bi-Level L1 Optimization- Based were applied. It was observed that all three methods successfully eliminate the interference without negatively impacting the target angle estimation. Additionally, the best Signal-to-Interference-and-Noise Ratio (SINR) was achieved by the Bi-Level L1 Optimization- Based, followed by the STFT and L-Statistics method.

4.3.5 Evaluation of the Method on Real Data

- **Acquisition of Real Data Used for Method Evaluation**

For evaluating the performance of the radio frequency interference mitigation methods presented in the previous section, radar data captures were performed using a DCA100EVM acquisition board and two FMCW AWR1843 radar sensors to obtain correlated interference, uncorrelated interference, and continuous interference.

Evaluation of the Performance of Radio Frequency Interference Mitigation Methods

In this section, we conducted a performance comparison of six methods (STFT and L-Statistics, Zeroing, Ramp Filtering, IMAT, Bi-Level, and Autoregressive) used for interference mitigation in FMCW radar. It was observed that, depending on the type and characteristics of the interference, certain methods may be more effective than others. Consequently, the choice of the optimal interference mitigation method should be tailored to the specific interference scenario encountered, to ensure the best results in terms of signal quality and radar system performance.

4.3.6 Real-Time Implementation and Evaluation of the Method

This section presents the implementation of the developed RFI mitigation method based on STFT and L-Statistics on the AWR1843 Single-Chip radar sensor and the results of tests conducted in a laboratory environment.

The main steps followed in the implementation of the STFT and L-Statistics-based method on the AWR1843 platform are illustrated in Figure 4.2.

4.4 Conclusions

This chapter introduces a new method for mitigating radio frequency interference (RFI) based on STFT and L-Statistics. The proposed method aims to effectively eliminate uncorrelated interference signals from the beat signal, thereby improving the overall signal quality and radar system performance. It has been demonstrated that the proposed method can mitigate multiple sources of interference with varying intensity levels. Additionally, it was observed that by selecting the window shift step to be half of its length, similar performance is achieved as when the window is shifted by a unit step, as per the classical definition of STFT. Furthermore, choosing this window shift step results in a significant reduction in processing/computation time, enabling the method to be implemented in real-time on a digital signal processor.

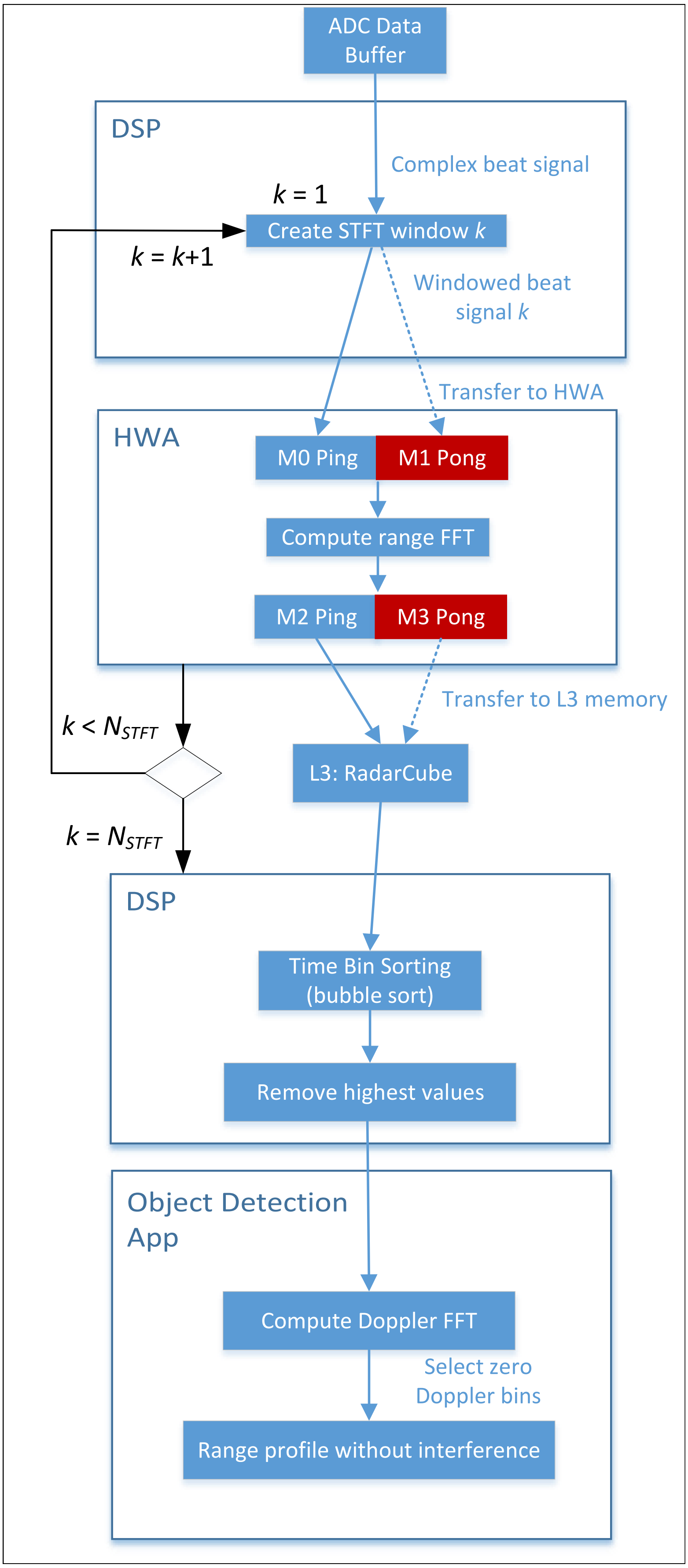


Fig. 4.2 Block diagram of the algorithm implemented in real-time on the AWR1843 radar

Chapter 5

Interference Mitigation Method Based on Polarization Rotation for FMCW Radars in the Automotive Domain

In this chapter, we present a study dedicated to mitigating radio frequency interference (RFI) in FMCW radar systems by using cross-polarized orientation between the victim radar's antennas and the interfering radar's antennas, in scenarios where the victim radar employs a MIMO configuration.

5.1 Types of Polarization

In FMCW radars, the polarization of electromagnetic waves can significantly influence system performance, particularly in terms of target detection and interference reduction:

Most FMCW radars use linear polarization, either vertical or horizontal. This simplifies radar design and the analysis of reflected signals. However, the exclusive use of linear polarization may limit the radar's ability to distinguish between different types of targets and to manage interference effectively.

5.2 Description of the Scenario Used for Data Acquisition

To analyze how the use of cross-polarization aids in mitigating and even eliminating mutual interference between FMCW radars used in the automotive industry, we utilized two AWR1843 radar systems and a DCA100 data acquisition board to collect data for various scenarios.

One of the radar units operated as the interference source, while the other radar unit served as the victim radar. Notably, the victim radar was systematically rotated in steps of 10 degrees, covering a total rotation of 90 degrees, to evaluate the impact of different orientations on susceptibility to interference.

5.2.1 Analysis of Results for Interference Suppression Achieved through the Application of the Method

In this section, the results obtained from applying the cross-polarization method for rotating the victim radar relative to the interfering radar in increments of 10 degrees, within the range of 0–90 degrees, will be presented.

To evaluate how polarization rotation reduces the effect of interference, we analyzed the range profiles of the beat signal affected by interference, obtained for each 10-degree rotation of the victim radar relative to the interfering radar, within the 0–90 degree range.

It was observed that the exclusive use of the polarization rotation method for interference mitigation enables a notable reduction in noise levels, exceeding 20 dB when the rotation angle of the victim radar surpasses 80 degrees.

5.2.2 Comparison of the Performance of the Proposed Method with Other Methods

In this section, the results obtained from applying the cross-polarization method both independently and in combination with two other interference mitigation methods—one operating in the time domain (Zeroing) and the other in the time-frequency domain (STFT and L-statistics)—will be presented.

It was observed that polarization plane rotation significantly enhances the efficiency of interference mitigation, improving the SINR by approximately 8 dB when the victim radar is rotated by 90 degrees. This result suggests that integrating polarization plane rotation with classical mitigation methods can provide effective solutions for managing interference in radar systems.

Chapter 6

Detection and Mitigation of Interference in Synthetic Aperture Radar

Detection and mitigation of interference in Synthetic Aperture Radar (SAR) systems represents a significant challenge in radar technology.

Interference can be caused by adjacent radars, communication equipment, or even natural phenomena. It manifests as an increase in background noise and distortion of useful signals, leading to errors in estimating the parameters of detected objects, such as position and velocity. Therefore, the implementation of efficient techniques for interference detection and mitigation is essential for improving the performance of SAR systems.

6.1 Methods for Radio Frequency Interference Mitigation in SAR

Various techniques have been developed to detect and mitigate the effects of interference in SAR images. Adaptive filtering has proven to be the most practical signal processing approach, characterized by its ability to design filters either in the frequency domain [20] or in the time-frequency domain [26].

Detecting interference in the time domain is quite challenging, especially when its level is similar to the echo from a target. However, by analyzing the interference-affected signal in the time-frequency domain, interference can be easily detected as its bandwidth is much narrower compared to that of the target-reflected echo signal.

In [14], an innovative method is presented that mitigates interference in three stages: Detection, Notch, and Recovery.

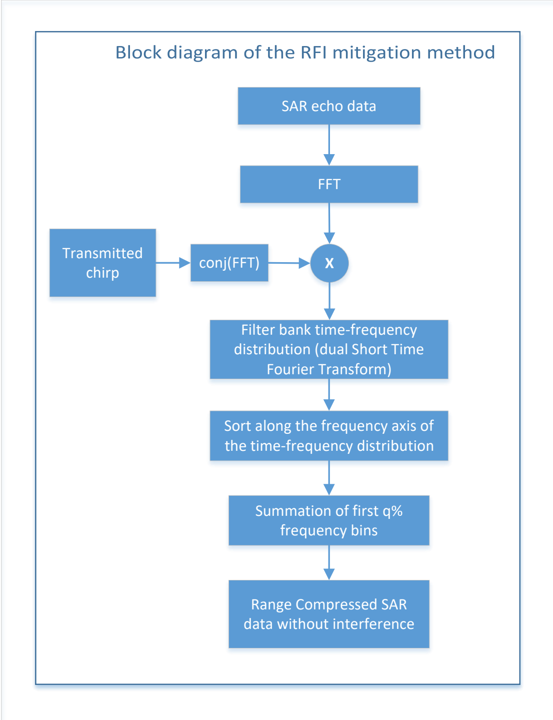


Fig. 6.1 Block diagram of the FB-TFD and L-Statistics method

6.2 Interference Suppression in SAR Using a Method Based on a Filter Bank Time-Frequency Distribution and L-Statistics

The interference suppression method for Synthetic Aperture Radar based on the use of a filter bank viewed time-frequency distribution (FB-TFD) and L-Statistics is a novel approach that I have developed, implemented, and presented in [18]. This method operates in the time-frequency domain and does not involve locating RFI in SAR echo data. Additionally, the method can theoretically suppress any interference signal uncorrelated with the transmitted chirp and does not require precise a priori knowledge about the type of RFI.

6.2.1 Description of the Method

The algorithm for the interference mitigation method using filter banks time-frequency distribution (FB-TFD) and L-Statistics is presented in Figure **??**. It can be observed that the echo signal from the SAR (from the acquisition matrix) serves as the input parameter for the method.

The first step in the processing chain involves generating the spectrum of the range-compressed signal. This is achieved by multiplying the spectrum of the SAR echo with the conjugate version of the transmitted chirp spectrum. Subsequently, FB-TFD with partially overlapping frequency bands is applied to the compressed signal spectrum over the range interval. Similar to the Short-Time Fourier Transform (STFT), FB-TFD can be considered an ordered collection of narrow-band frequency signals in the time domain [8] (such a signal is obtained via an inverse FFT of the range-compressed spectrum, truncated by a narrowband filter applied in the spectral domain). After range compression, the signature of a target in the FB-TFD matrix appears as a constant line in time across all frequency bins (it is stationary in the time-frequency plane).

Assuming that the interference signal is uncorrelated with the transmitted chirp (for example, a chirp with a different slope), the interference will exhibit a non-stationary signature in the FB-TFD of the range-compressed signal.

The next step in the processing chain for the interference-affected signal involves sorting each constant time line in the time-frequency distribution matrix in ascending order, which places the interference in the higher end of the time-frequency plane.

Subsequently, the interference-free range profile is obtained by coherently summing along the frequency axis the first $q\%$ of frequency bins from the sorted distribution (bins identified as unaffected by interference).

6.2.2 Experimental Results

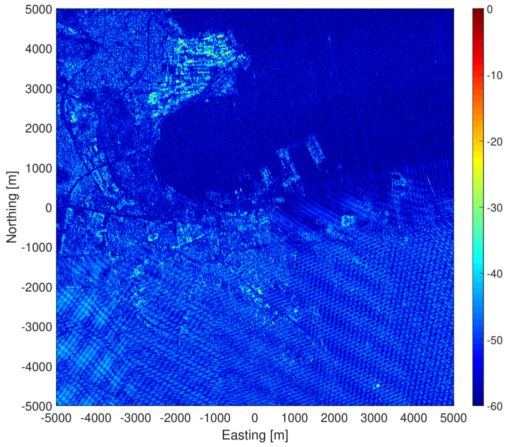
The proposed method was tested on raw SAR data affected by radio frequency interference, captured by the Sentinel-1 satellite over Doha, Qatar, on April 26, 2021.

According to [3], the source of the interference was a radar from the Patriot Missile System operating in Damman, Saudi Arabia. When a radar system operates in the C-band, Sentinel-1 receives not only the reflection of its emitted radio waves but also the radio waves emitted by the ground-based radar. This typically manifests as a bright band of interference in the SAR image, perpendicular to the satellite's orbital trajectory.

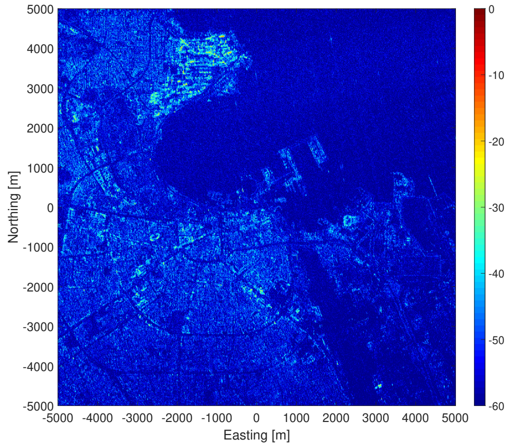
Figure 6.2a, which illustrates the case with interference, clearly shows that the interference affects the southern part of Doha. In contrast, Figure **??** demonstrates the success of applying the proposed FB-TFD method for interference suppression in the region affected by RFI.

6.2.3 Comparison of Interference Mitigation Performance: FB-TFD and L-Statistics versus Zeroing

The performance comparison between the FB-TFD-based method and the Zeroing method was conducted by comparing the spectrum of the signals obtained after applying the methods, as illustrated in Figure **??**. Here, it can be observed that both methods reduce interference; however, the FB-TFD method produces better results compared to the Zeroing method.



(a)



(b)

Fig. 6.2 Focused image from the Sentinel-1 dataset acquired on 26.04.2021 over the city of Doha, Qatar: (a) with interference, (b) without interference.

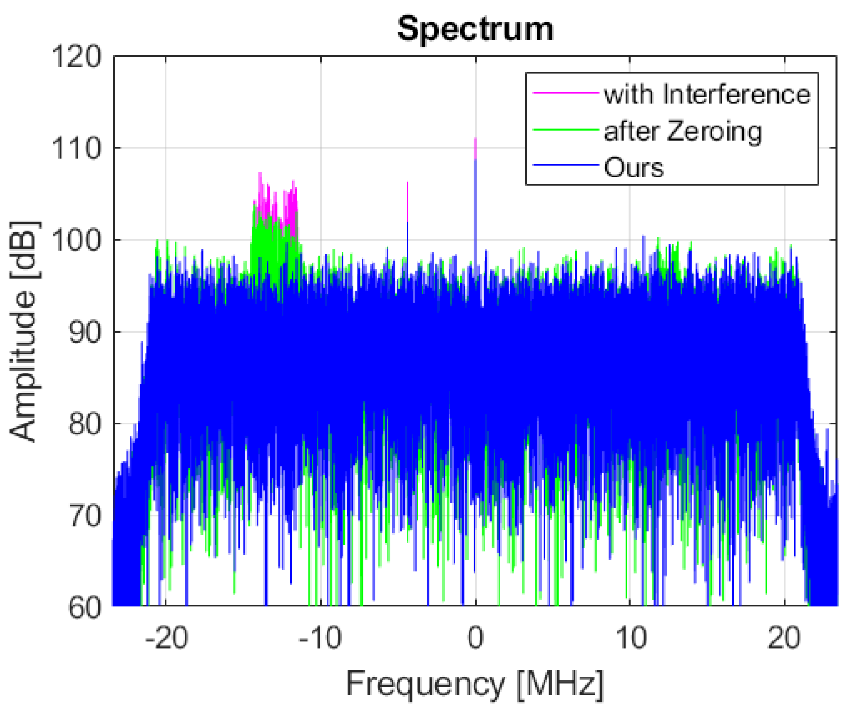


Fig. 6.3 Range-compressed signal spectrum before and after applying the FB-TFD and Zeroing methods.

Chapter 7

Conclusions

In this thesis, we addressed the challenges related to interference in FMCW and SAR radars, emphasizing the importance and complexity of managing these issues in automotive applications and the numerous other applications where Synthetic Aperture Radar is utilized.

For FMCW radar, interference can induce measurement errors by overlapping reflected signals, potentially leading to false target detection or increased noise levels. In the case of SAR, interference can degrade image quality by distorting signals, reducing the clarity and resolution of the final image.

In this thesis, we presented a series of methods and algorithms that contribute to reducing the impact of interference, including signal analysis-based detection and suppression techniques, as well as approaches leveraging polarization rotation.

We also examined the effects of these methods on the accuracy and reliability of measurements, highlighting how the proposed solutions can effectively address interference challenges encountered in FMCW and SAR radars.

7.1 Obtained results

In **Chapter 4**, a new method for interference mitigation in FMCW radar for the automotive industry is presented. This method was published in [16] and [17] (after the method was implemented in real-time on the AWR1843 radar sensor).

In **Chapter 5**, a method for interference mitigation based on polarization rotation is presented, which was published in [19].

In **Chapter 6**, a new method for interference mitigation in SAR is proposed, based on FB-TFD and L-Statistics. The method was published in [18], where its effectiveness was demonstrated in improving the quality of C-band SAR images from Sentinel-1 affected by interference originating from a ground-based radar component of the Patriot Missile System.

7.2 Original contributions

1. I developed a new method for mitigating radio-frequency interference in FMCW radars for the automotive industry, based on Short-Time Fourier Transform and L-Statistics. The method was presented at the Radar Conference in New York in 2022 [16].

2. I conducted a comparison of the performance of six radio-frequency interference mitigation methods for FMCW radars in the automotive industry. The results were published in [15].

3. I implemented in real-time the method based on Short-Time Fourier Transform and L-Statistics on the AWR1843 radar sensor [17].

4. I analyzed how interference is mitigated using the polarization rotation-based method and conducted an analysis of the combined operation of analytical methods with the polarization-based method. The method was presented at the ATOMS2024 conference, where the paper received the "Excellent Paper" award [19].

5. I developed a new method for mitigating interference in Synthetic Aperture Radar (SAR) based on FB-TFD and L-Statistics. The method was presented at the IGARS2024 conference [18].

7.3 List of original publications

1. R. Muja, A. Anghel, R. Cacoveanu and S. Ciochina, "Interference Mitigation in FMCW Automotive Radars using the Short-Time Fourier Transform and L-Statistics," 2022 IEEE Radar Conference (RadarConf22), New York City, NY, USA, 2022, pp. 1-6, doi: 10.1109/RadarConf2248738.2022.9764271.

2. R. Muja, A. Anghel, R. Cacoveanu and S. Ciochina, "Assessment of RF interference mitigation methods for automotive radars using real data," 2022 14th International Conference on Communications (COMM), Bucharest, Romania, 2022, pp. 1-5, doi: 10.1109/COMM54429.2022.9817371.

3. R. Muja, A. Anghel, R. Cacoveanu and S. Ciochina, "Real-Time Interference Mitigation in Automotive Radars Using the Short-Time Fourier Transform and L-Statistics," in IEEE Transactions on Vehicular Technology, doi: 10.1109/TVT.2024.3400625.

4. R. Muja, A. Anghel, R. Cacoveanu and S. Ciochina, "SAR Interference Mitigation using a Filter Bank Time-Frequency Distribution and L-Statistics," IGARSS 2024 - 2024 IEEE International Geoscience and Remote Sensing Symposium, Athens, Greece, 2024, pp. 7938-7942, doi: 10.1109/IGARSS53475.2024.10641830.

5. R. Muja, A. Anghel, and S. Ciochina, "RFI mitigation method based on polarization rotation for automotive FMCW radars," ATOMS 2024 - The 2024 IEEE Conference on Advanced Topics on Measurement and Simulation, 28-30 August, 2024, Constanța, Romania.

7.4 Perspectives for further developments

The following section will present five main research directions aimed at optimizing and adapting interference mitigation methods in FMCW and SAR radar systems. Each of these directions proposes an innovative approach that could lead to significant advancements in interference suppression for FMCW and SAR radars.

1. **Optimization of the STFT and L-Statistics Method Using Different Types of Windows:** Investigating how the choice of various window functions impacts the performance of the STFT and Order Statistics-based method, aiming to further enhance interference suppression efficiency.

2. **Evaluation of Real-Time Implementation of the STFT and L-Statistics Method with LIDAR Sensor Integration:** Assessing the real-time performance of the method when integrated with a LIDAR sensor, potentially improving accuracy and robustness in interference-rich environments.

3. **Performance Analysis of the Polarization-Based FMCW Radar Interference Mitigation Method in the Presence of Correlated Interference:** Evaluating the effectiveness of the polarization rotation method under scenarios with correlated interference to better understand its limitations and advantages.

4. **Application of the FB-TFD and L-Statistics Method to Focused SAR Images:** Extending the use of the FB-TFD and L-Statistics method to mitigate interference directly on focused SAR images, potentially improving final image quality.

5. **A Detailed Comparison of the Performance of the FB-TFD and L-Statistics Method with Other State-of-the-Art Methods for SAR Radar Interference Suppression:** Conducting a comprehensive comparative analysis to benchmark the FB-TFD method against other advanced techniques, highlighting its strengths and identifying areas for improvement.

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