# 1. Assessing Power Amplifier Distortions on Radar Waveforms for Spectral Coexistence

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**Abstract:** *This chapter deals with the effects of Power Amplifiers (PAs) on radar waveforms designed to ensure spectral compatibility with other Radio Frequency (RF) wireless systems cohabitating in the same frequency band. To this end, a specific hardware-in-the-loop test-bed composed of a Personal Computer (PC), an Arbitrary Waveform Generator (AWG), a nonlinear PA, and a Signal Analyser (SA) is designed. It allows to gather measurements of the amplified signal and to grasp unwanted modifications of its spectral features due to the PA nonlinear distortion. Besides, it permits a quantitative assessment of the discrepancies between the nominal and the actual interference power injected by the radar in the shared frequency bandwidths. To alleviate the spectral distortions induced by the PA and improve spectral coexistence, the use of a Digital Pre-Distortion (DPD) stage upstream the PA is investigated. Modeling techniques together with parameters inference are discussed and applied to the measured waveforms. The obtained experimental results highlight that pairing a suitable waveform design strategy with a DPD processing represents a viable means to mitigate the PA distortions and to realize spectral coexistence.*

## 1.1 Introduction

Power Amplifiers (PAs) represent the block of the radar transmit chain which drives the transmit antenna. Conceptually, a PA is an active electronic device that provides at its output an amplified and undistorted version of its low-power Radio Frequency (RF) input waveform. Unfortunately, from a practical point of view, a PA is not able to maintain constant gain and exhibit nonlinear behaviours that induce both in-band and out-of-band distortions on the amplified signal [1–3].

Such distortions can significantly impair the expected performance of the system, especially in radar applications involving spectrum sharing strategies to enable the cohabitation among the radar and other telecommunication systems operating within the same frequency band [4–6]. Indeed, out-of-band spurious components could potentially degrade performance of the systems operating over the frequency bands adjacent to that occupied by the radar. Moreover, if the designed radar waveform encompasses the presence of notches in the frequency spectrum, the in-band distortion could seriously compromise the nulls' depth leading to degradations in terms of spectral compatibility with overlaid systems [6–9].

To face with the undesired PA effects, several signal processing strategies have been proposed during the last years [1]. Among them, Digital Pre-Distortion (DPD) has gained wide attention in both radar and communication practice [10–15]. It relies on a suitable

# 2. Radar Clutter as a Communications-Enabling Ambient Signal

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**Abstract:** *Radar systems - especially when undertaking search functions - always generate reverberation from the surrounding environment, referred to as* clutter *in Radar parlance. This chapter shows that ground clutter - produced by stationary reflectors located in the patrolled region - enables data delivery from a sender, also referred to as a* tag*, to a receiver (referred to as a* Reader*). In particular, we show that the tag - which is only enabled to vary the amplitude and/or the phase of the incoming signal - may modulate the clutter returns adopting diverse modulation schemes, the only limitation being that the length of the transmitted frame be smaller than the ground clutter coherence time. Sample plots of the performance achievable through two simple modulation schemes are also offered to show the feasibility of the proposed architecture.*

## 2.1 Introduction

The fast development of such ideas as Internet of Things, perceptive mobile networks aimed at offering new advanced applications,"smart cities", and so on has inevitably produced spectrum overcrowding: in short, communications - in their need for larger and larger transmission bandwidths - have been migrating towards frequency bands traditionally assigned to sensing. The issue of coexistence between sensing and communications has thus soon led to "convergence" between these two functions and to a paradigm shift from the traditional spectrum sharing architecture towards Integrated Sensing And Communication (ISAC): A single active transmitter and two or more different receiving chains are designed so as to accommodate the two functions, possibly prioritizing one of the two or else assigning them equal dignity [1, 2].

A far less costly strategy relies on the exploitation of signals of opportunity—typically, the signal emitted by TV/FM towers, cellular base stations, and Wi-Fi access points—to implement a passive radar, which has the merit of being low-cost, difficult to jam, easy to deploy, and undetectable [3]. To the family of passive radars can be somehow ascribed the *opportunistic* architectures considered in [4, 5, 6, 7], mainly with reference to automotive applications through millimeter-wave (mmWave) communication signals: in close proximity with the communication transmitter, a radar receive chain, which may avail itself of information shared by the transmitter, implements the sensing function without producing interference and without requiring any additional physical resource. In particular, [8] puts forward mmWave communication signals as the only credible means to support massive automotive sensing.

In this chapter we focus on the little explored concept of radar-enabled communications, wherein radar reverberation is used as a carrier signal [9]. Any object located inside a scene illuminated by a radar transmitter inevitably produces scattering in all

# 3. OFDM Radar based on communication signals of opportunity

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**Abstract:** *This chapter illustrates innovative signal processing techniques and architectures for radar systems based on the exploitation of opportunistic communication signals, namely WiFi and DVB-T OFDM signals. It covers three different applications and operational scenarios where these systems can be effectively employed for surveillance purposes, namely (i) short range monitoring based on WLAN transmissions, (ii) radar systems on board of moving platforms, and (iii) low-cost forward scatter radar sensors for distributed surveillance of designed areas. In all cases, the peculiar characteristics of the considered application are discussed, and ad hoc solutions are proposed. While the proposed approaches can be exploited in both active and passive radar systems, the discussion is supported by experimental results obtained using passive radar prototypes either developed at Sapienza University of Rome or by research partners. This gives the opportunity to understand the benefits of these approaches in real world scenarios and to demonstrate their effectiveness against experimental datasets.*

## 3.1. Introduction

OFDM radar uses an Orthogonal Frequency Division Multiplexing (OFDM) signal as radar waveform. The advantages of OFDM modulation are well established in communication systems, where its use has been consolidated since decades [1]. In contrast, the interest in OFDM techniques for radar applications has appeared relatively recently [2]. However, its popularity has increased rapidly being driven by the advancement in hardware capabilities and the growing demand for RF spectral resources.

Specifically, the latter aspect was dealt with from two different perspectives.

On one hand, several studies have addressed the possibility to exploit parasitically OFDM transmitters of communication systems as illuminators of opportunity for passive radar (PR) [3]-[14]. These included popular state-of-the-art broadcast technologies such as DVB-T (Digital Video Broadcasting – Terrestrial) and DAB (Digital Audio Broadcasting) [3], [6], [8]-[10], but also the transmitters for metropolitan and local area networking (e.g. Long-Term Evolution – LTE – 5G, WiFi), which are proliferating at rapid rate [11]-[14]. This approach makes available a wide set of energy sources that could enable the implementation of PR for the surveillance of wide areas as well as for short range monitoring applications, provided that appropriate signal processing techniques are used to mitigate the effects of the OFDM waveform characteristics which are not under control of the radar designer.

Another interesting perspective used in OFDM radar research is concerned with the emerging technology of joint radar and communication (JRC) or integrated sensing and communication

# 4. A mitigation approach for Radio Frequency Interferences corrupting airborne FMCW SAR data

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***Abstract.*** *In this work we focus on the mitigation of Radio Frequency Interferences (RFI) corrupting airborne Synthetic Aperture Radar (SAR) data.*
*To this aim, we propose a two-step processing procedure for the RFI identification, which is able to work on range compressed (RC) SAR signals.*
*The devised methodology is specifically tailored to RC data including radar samples gathered prior to the reception of the nadiral echoes, that is before receiving the signals backscattered from the observed scene. It is worth noting that such a situation is quite common for a wide class of airborne SAR sensors conceived to operate at different flying altitudes, thus allowing the flexible setting of the radar reception window.*
*In particular, the first processing step of the proposed methodology is aimed at providing a ballpark indication on the amount of SAR signals corrupted by the interferences, by means of the analysis of the radar data where the backscattering contribution is absent. Such an information is used to tune the second processing step, which provides detection decisions based on the results of statistical hypotehesis tests carried out on the backscattering data.*
*The acheivable detection maps are then exploited to drive a simple, but effective, RFI suppression procedure that treats as missing data the samples of the RC image that have been detected as interfering signals.*
*The perfomance of both steps of the proposed RFI identification methodology has been assessed by means of simulated data.*
*In addition, the overall RFI mitigation approach has been applied to real-world L-band full-polarimetric SAR data corrupted by interferences, which have been collected by the Italian airborne Multiband Interferometric and Polarimetric SAR (MIPS) system based on the Frequency-Modulated Continuous Wave (FMCW) technology. The presented experimental results confirm the effectiveness of the proposed approach in recovering the radar data information content.*

# 5. Continuous-Emission Noise Radars: a Tool for an Efficient and Secure Use of the Electromagnetic Spectrum

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**Abstract:** *Noise Radar Technology (NRT) can be used to ensure an "efficient" exploitation of the electromagnetic spectrum for civil applications and a "secure" use of it in the military arena. By the term "efficient", we mean the coexistence of different sources at the same time in the same band, overcoming the interference problem when the e.m. spectrum is shared. By the term "secure", we mean the resistance of the radar waveforms to detection, interception and exploitation by an enemy. In this frame, the radar system transmits signals with low-probability of detection (LPD), interception (LPI) and exploitation (LPE) capabilities. After a description of the main requirements for the implementation of a noise-like waveforms generator, the "efficient" feature is treated in the context of marine radars. The most significant part of the chapter is focused on the "secure" feature, analyzing the capability of NRT against modern electronic warfare intercept receivers (Electronic Support Measures – ESM or Electronic Intelligence – ELINT) based on time-frequency processing. In order to characterize these capabilities, we discuss the performance aspects of time-frequency processing aimed at the extraction of spectral parameters of Noise Radar waveforms, with presentation of preliminary experimental results.*

## 5.1. Introduction

Since the early days of radar applications, particularly in the military arena, it was clear that the performance of a radar system strongly depends on the transmitted signal (and on the antenna pattern). Hence, the design of more and more sophisticated waveforms (suitable for different applications) has rapidly developed, as evidenced by the publications of seminal books [1]-[3] on radar signals, and by the so many papers in the literature on radar waveform design and evaluation showing a very widespread scientific and technical activity till today.

Conventional solutions to overcome the interference problem are the well-known approaches based on the concept of *"diversity"*: in *frequency*, *space*, *time*, *polarization* and *code*. It is in the nature of things, that *random signals* are inherently *code-orthogonal* to any other signal; hence, it makes their usage as radar waveforms a favourable choice.

However, the spectral efficiency and the rejection of mutual interference are not the only advocate for noise radar technology. A second and very important feature is their resilience against electronic warfare (EW). Focusing the attention on the Electronic Defence (ED) arena [4]-[7], where modern countermeasures have matured from simple barrage noise jamming towards *smart jamming*. These *"smart"* techniques aim at a situation in which the radar operator is unable to distinguish between real targets and a manifold of false but realistic targets. Jamming techniques of that kind require the Electronic Defence (ED) system to observe, record, manipulate and re-tranmit the signals of the radar to be jammed.

# 6. Sequential Convex Approximation based MIMO Radar Beampattern Design with Multi-Spectral Constraints

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**Abstract:** *This chapter deals with the multiple-input–multiple-output (MIMO) radar beampattern design in an effort to the coexistence with multiple communication systems. A waveform optimization model accounting for the minimization of the beampattern integrated sidelobe level (ISL) along with the mainlobe width, peak-to-average power ratio, and energy constraints is established. Besides, multi-spectral requirements are precisely controlled to ensure the desired quality of service at each communication system in each shared frequency band and particular directions. Through an equivalent reformulation of the original nonconvex problem, a polynomial-time sequential convex approximation (SCA) procedure that involves the tackling of a series of constrained convex problems is proposed to monotonically decrease the ISL with the convergence guaranteed to a Karush–Kuhn–Tucker point. Herein, to speed up the convergence, a fast iterative algorithm based on the alternating-direction-method-of-multipliers framework is introduced to globally solve the convex problems during each iteration of the SCA procedure. Numerical results are provided to assess the proposed algorithm in terms of the computational complexity, the achieved beampattern, and spectral compatibility with some competitive counterparts available in the open literature.*

## 6.1 Introduction

Beampattern formation has been a long-standing and significant topic in the radar signal processing field due to its ability to concentrate the radiation power in a spatial region of interest while reducing interference returns and improving target detectability [1, 2]. Colocated Multiple-Input Multiple-Output (MIMO) radar offers the potential advantage in shaping a suitable beampattern over its phased array counterpart via waveform diversity using various waveform optimization design methods [3–6]. In this respect, MIMO radar transmit beampattern design has drawn a lot of interest in the radar signal processing community [7–9].

Two different optimization schemes are widely exploited to attain a desired MIMO transmit beampattern. The former adopts a two-phase process that includes the optimization of the waveform covariance matrix to achieve a desired beampattern, then the synthesis of the probing waveforms to approximate the covariance matrix with some practical waveform constraints [10–17]. For instance, in [10], beampattern matching design with respect to the waveform covariance matrix is addressed by jointly minimizing beampattern approximation error and the cross-correlation of the signals returning back to the

# 7. Waveform Design in MIMO Radars for Range-ISL Minimization and Spectral Compatibility

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**Abstract:** *This chapter tackles the challenge of waveform design for Multiple-Input Multiple-Output (MIMO) radar systems that are colocated, aiming to minimize the range-Integrated Sidelobe (ISL) while achieving spectral compatibility with a suitable spectral response. To accomplish this, a discrete phase constraint is imposed on the optimization problem. The range-ISL function is initially defined in the time domain, representing the level of interference caused by the radar waveform at different ranges. To achieve spectral compatibility, the range-ISL function is transformed into the frequency domain using the Parseval relation, which permits the use of weights to control the amount of interference in different frequency bands. However, this results in a challenging optimization problem that is NP-hard, multi-variable, and non-convex, requiring an iterative approach to find a local optimal solution. To address this, we propose an iterative approach based on the Coordinate Descent method, which optimizes one coordinate of the solution vector while holding the others fixed. This approach enables a more efficient search of the solution space and helps balance the trade-offs between the competing objectives and constraints. The proposed approach can provide valuable insights into the challenges and solutions associated with waveform design for range-ISL minimization with spectral compatibility in MIMO radar systems. By minimizing the range-ISL while achieving spectral compatibility, the radar system can detect targets at longer ranges while reducing making interference to other systems, such as communications. This is particularly useful for applications that require the co-existence of communications and radar systems, such as surveillance and automotive radar systems.*

## 7.1 Introduction

With the increasing demand for wireless services, the available spectrum is becoming more and more crowded, leading to interference and reduced quality of service. Fortunately, regulators are exploring various solutions to tackle this issue and increase capacity. One promising solution is to incorporate advanced wireless technologies, including Multiple-Input Multiple-Output (MIMO), beamforming, and cognitive radio. These technologies can enable more efficient use of the available spectrum and help ease the congestion problem.

Similar to wireless communication systems, radar systems also face challenges when dealing with concurrent transmissions from other Radio Frequency (RF) systems. To address this, spectrum sharing between radars and communication systems has become a highly plausible scenario, paving the way for new opportunities and collaborations [1]. With recent advancements in this field, the integration of radar and communication

# 8. Assessment of UAV-Based ISAC SAR Imaging: Techniques and Performance Evaluation

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**Abstract:** *This chapter aims to showcase the capabilities of an Integrated Communication and Sensing (ISAC) system, which operates within the sub-6 GHz frequency range, for Synthetic Aperture Radar (SAR) imaging from an Unmanned Aerial Vehicle (UAV). The primary objective of this study is to assess the feasibility of producing SAR imagery while meeting practical constraints set by contemporary communication standards. These constraints encompass parameters such as maximum transmitted power, carrier frequency, occupied bandwidth, Pulse Repetition Frequency (PRF), the number of sub-carriers utilized, and more. The chapter furnishes a comprehensive explanation of the Orthogonal Frequency Division Multiplexing (OFDM) signal transmitted by the base station. Additionally, it compares two potential methods for range-compressing the signal in terms of Integrated Side Lobe Ratio (ISLR) and Peak-to-Sidelobe Ratio (PSLR). An examination of the Noise Equivalent Sigma Zero (NESZ) is proposed under both classical line-of-sight conditions and in more demanding environments, showcasing the system's ability to detect targets even under snow cover. The conclusion encompasses the presentation of simulated Impulse Response Functions (IRF) under various assumptions, alongside actual SAR images of the environment captured using a UAV equipped with a software-defined radar (SDR).*

## 8.1 Introduction

Traditionally, wireless communication and radar have operated as separate systems with distinct hardware, waveforms, and objectives. While wireless communication focuses on information transport, radar systems are primarily used for environment sensing. However, the advent of sixth-generation (6G) cellular networks introduces a new perspective where sensing complements communication, forming Integrated Sensing and Communication (ISAC) systems [1, 2].

### 8.1.1 Overview of ISAC

The integration of radar sensing into communication systems poses a significant challenge for ISAC. Various efforts have been made to develop combined radar and communication systems [1, 2].

Incorporating communication into radar systems requires embedding communication signals into radar emissions with minimal interference. Previous studies have explored methods such as selecting radar waveforms representing communication symbols for dual functionality [3]. While radar systems offer advantages for long-range communication due to their extensive operational range, their capacity is often limited by inherent waveform constraints.