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System and Circuit Design for Accurate Frequency-Modulated Continuous-Wave Local Positioning Radars

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SYSTEM AND CIRCUIT DESIGN FOR ACCURATE FREQUENCY-MODULATED CONTINUOUS-WAVE LOCAL POSITIONING RADARS

Mohammed El-Shennawy

von der Fakultät Elektrotechnik und Informationstechnik
an der Technischen Universität Dresden
zur Erlangung des akademischen Grades

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Abstract

This work presents the system and circuit design, modelling and optimization of a frequency-modulated continuous-wave (FMCW) indoor positioning radar operating at the 2.4 and 5.8 GHz industrial, scientific and medical (ISM) bands.

Various non-ideal effects on FMCW radar ranging precision and accuracy are modelled and investigated such as crystal oscillator (XO) tolerance, receiver (RX) thermal noise, fractional-N phase-locked loop (Frac-N PLL) phase noise and systematic chirp nonlinearity.

Optimization techniques are proposed to the Frac-N PLL for highly linear wideband chirp generation. Verilog simulations as well as measurement results confirm a low root mean squared (RMS) chirp nonlinearity error of 14.6 kHz.

A single-ended low-noise amplifier (LNA) design alleviates the need for an external passive balanced-to-unbalanced (balun) converter. A gain interpolating variable gain amplifier (VGA) architecture is used and simple techniques are proposed to improve the input signal handling capability and VGA linearity. A baseband detector architecture is introduced with a detection accuracy of ±0.15 dB. The high accuracy is attributed to the use of an inherent process, voltage and temperature (PVT) cancellation concept.

A nonlinear model for the automatic gain control (AGC) loop relying on simple and readily available components from the *"analogLib"* and *"functional"* libraries is built in the CADENCE design environment. The model provides insights into system level parameters such as AGC loop bandwidth, phase margin, settling time as well as estimating the AGC dynamic range and received signal strength indicator (RSSI) voltage vs. input power.

Measured in lab conditions, the developed transceiver (TRX) chip achieves a ranging precision of 0.3 and 5.2 mm in primary and secondary radar configurations, respectively. Indoor ranging precision is measured to be between 1.2 and 1.5 cm while the RMS indoor ranging error is at 17 cm.

When used for a practical indoor positioning scenario, the system achieves an RMS tracking error of 10 cm which competes with more sophisticated state-of-the-art multiple-input multiple-output (MIMO) based local positioning systems incorporating a larger number of transmitters (TXs), RXs and base stations (BSs).

Table of Contents

Chapter 1

Introduction

This chapter explains the motivation behind this work, briefly introducing the main concepts and architectures used and presenting the thesis scope, objective and outline.

1.1. Motivation

The European seventh framework research project "MAGELLAN" [MAG] aims at the development of cost-effective solutions for the authoring and experiencing of next-generation location-based experiences. With the development of the MAGELLAN authoring tool, creative designers and hobbyists with minimal computer science background could create their own experiencing scenarios and publish them as smartphone applications for others to download via the mobile application stores. One popular gaming experience for example is an outdoors treasure hunt such as Pokémon Go which appeared in summer 2016.

Beside the ability to author one's own experiences, the MAGELLAN project further aims at extending the already existing outdoor location-based experiences (mainly relying on the global positioning system (GPS) [NAV] for outdoor localization) to include also indoor experiences based on indoor positioning and tracking technologies as shown in Figure 1-1.

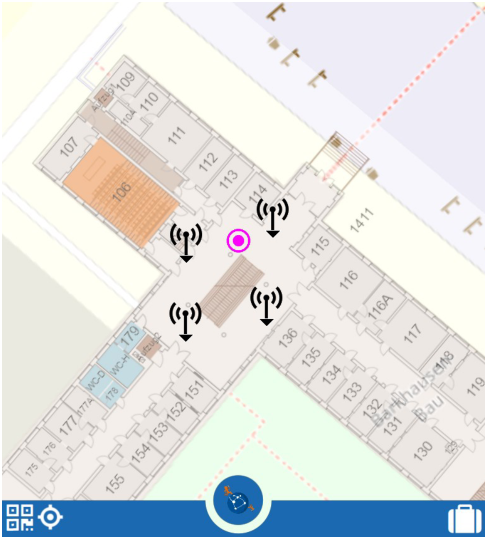

Figure 1-1 Mobile snapshot of a MAGELLAN indoor tracking application

Among many others, one use case would be to help users navigate their way in large shopping malls for example as they would normally do outdoors using GPS. Another use case could be the creation of fully automated guided tours in museums where an audio guide explains the current displayed items to the visitors based on the knowledge of their location in the museum without the need for entering an item number or scanning a QR code which makes the overall experience more pleasant for the visitors.

The MAGELLAN consortium includes 3 industrial partners, 5 end-user partners and 5 academic partners namely:

EXUS, *Greece*: Industrial partner and project coordinator, responsible for technical specifications, design and implementation of the MAGELLAN web platform, integration of technical results, evaluation of the project results and preparation of commercial exploitation.

Diginext, *France*: Industrial partner responsible for technical project management, technical specifications, design and implementation of the MAGELLAN authoring tool and mobile applications, integration of technical results and preparation of commercial exploitation.

Immersion, *France*: Industrial partner contributing to the implementation of the multimodal natural user interfaces of the authoring tool.

Naftemporiki, *Greece*, Mudlark, *UK*, FatDUX, *Czech Republic*, Functiona, *Spain* and Kreait, *Germany*: End-user partners contributing to the definition of the end-user requirements, the definition of concepts and scenarios and the implementation of the pilot demonstrators.

University of Nottingham, *UK*: Contributing to the end-user requirements, functional specifications, scenario creation and to the production of the guide for authors of location-based experiences.

Coventry University, *UK*: Contributing to the end-user requirements, functional specifications, scenario creation, and to the production of the guide for authors of location-based Experiences as well as the coordination of the training and pilot production activities.

TU Graz, *Austria*: Implementation of the augmented reality components and mobile interface and contribution to the implementation of the authoring tool.

EPFL, *Switzerland*: Implementation of augmented reality 3D video.

And finally, **TU Dresden, *Germany*:** Is responsible for the research and development of the localization systems of the project using multiple signals and standards such as GPS for outdoors and wireless local area network (WLAN), ZigBee, ultra-wide-band (UWB) radar and FMCW radar for indoors.

The targeted specifications for the indoor localization system prototypes to be developed within the MAGELLAN project are as follows:

Parameter	Spec	Unit
Operating Frequencies	2.4 and 5.8	GHz
RMS Tracking Error	0.5	m
Coverage Area	200	m^2
Operation Time with Battery	10	Hours
Prototyping Cost	1300	€/Station
Mass Fabrication Cost	110	€/Station

Table 1-1 Targeted indoor localization specifications

1.2. Scope, Objectives and Thesis Outline

The scope of this thesis is the circuit and system design of FMCW indoor positioning radars. The knowledge acquired by TU Dresden in the field of FMCW radars within the European project “E-SPONDER” [E-SP, Joram15] serves as an excellent starting point for this work.

For example, dual-band operation has proven to be beneficial in providing redundant sources of ranging information thus improving positioning accuracy. Therefore, dual-band operation is also adopted throughout this work.

The objective of this work is to build on the results obtained from the E-SPONDER project to further enhance the circuit and system design to provide a more robust and highly integrated FMCW indoor positioning system. Furthermore, several FMCW radar non-idealities are studied and investigated to determine whether the fundamental limits of the radar dictated by circuit level parameters such as XO tolerance, thermal noise and phase noise has been already reached or if there are still further implementation issues that hinder the performance.

This thesis is organized as follows: In the next sections, some basics of FMCW radars that will be used throughout the thesis are explained. In chapter 2, the radar TRX system design is explained in more detail and the fundamental limitations of XO tolerance, thermal noise and phase noise on FMCW radar accuracy and precision are investigated. In chapter 3, the TX side is optimized using synchronization and equalization techniques for more robust FMCW chirp generation. Then in chapter 4, the improvements on the RX side are presented including the design of a single-ended LNA, an integrated linear-in-dB baseband VGA, an integrated accurate baseband detector and an AGC loop. Finally, practical ranging and positioning measurement results are presented in chapter 5.

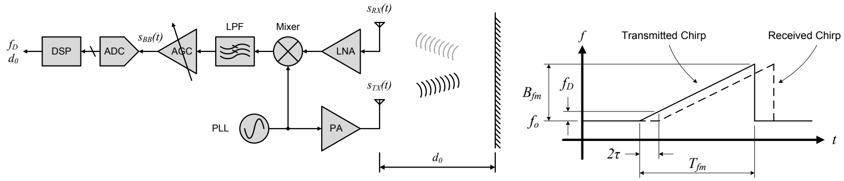

Figure 1-2 FMCW priamary radar block and timing diagrams

1.3. Primary FMCW Radar

The basic ranging signal in FMCW radars is the frequency ramp "the chirp" which is basically a constant amplitude sinusoidal signal whose instantaneous frequency is swept linearly over a bandwidth B_{fm} in a time T_{fm} as shown in the timing diagram in Figure 1-2 and is described as:

$$s_{TX}(t) = A_{TX}\cos\left(2\pi f_o t + \frac{B_{fm}}{2T_{fm}}t^2 + \varphi_{TX}\right), \tag{1.1}$$

where A_{TX} is the signal amplitude at the TX output, f_o is the chirp starting frequency and φ_{TX} is an arbitrary starting phase.

In primary FMCW radars, the chirp is transmitted, propagated at the speed of light c, hits the target after a time-of-flight (ToF) τ and bounces back to be received by the transmitting station after the same ToF as shown in the block diagram in Figure 1-2. The received signal at the RX can therefore be expressed as:

$$s_{RX}(t) = A_{RX}\cos\left(2\pi f_o(t-2\tau) + \frac{B_{fm}}{2T_{fm}}(t-2\tau)^2 + \varphi_{RX}\right), \tag{1.2}$$

where A_{TX} and φ_{RX} are the signal amplitude and phase at the RX input, respectively.

Assuming that the amount of delay in the power amplifier (PA) is negligible compared to the ToF and assuming that the radio frequency (RF) front-end composed of the LNA and mixer has a conversion gain (CG) equal to A_C, after mixing with the original transmitted chirp, the baseband signal can be expressed as:

$$\begin{aligned} s_{BB}(t) = \frac{1}{2}A_C A_{RX}\Bigg[&\cos\left(2\pi\left(\frac{B_{fm}2\tau}{T_{fm}}t + f_o\tau + \frac{B_{fm}(2\tau)^2}{2T_{fm}}\right) + \varphi_{TX} - \varphi_{RX}\right) \\ &+ \cos\left(2\pi((2f_o - \frac{B_{fm}2\tau}{T_{fm}})t + \frac{B_{fm}}{T_{fm}}t^2 - f_o\tau + \frac{B_{fm}(2\tau)^2}{2T_{fm}}) + \varphi_{TX} + \varphi_{RX}\right)\Bigg]. \end{aligned} \tag{1.3}$$

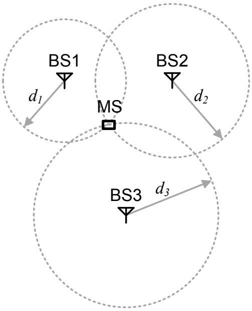

Figure 1-3 Target positioning using triangulation

It can be now seen from equation (1.3) that the resulting signal is composed of two components: First, a high frequency component at almost double the chirp starting frequency i.e. $2f_o$ with a chirp at double the original chirp slope i.e. $2B_{fm}/T_{fm}$. This component is easily filtered out by the low-pass filter (LPF) in Figure 1-2. And second, a low frequency baseband component whose frequency, f_D, is equal to the frequency difference between the transmitted and received chirps and therefore related to the round-trip time-of-flight (RToF) as:

$$f_D = \frac{B_{fm} 2\tau}{T_{fm}}. \tag{1.4}$$

Therefore, after digitizing the down-converted baseband signal by means of an analog-to-digital converter (ADC), a digital signal processing (DSP) unit could evaluate the value of the baseband frequency f_D and thus the range, d_o, as described by:

$$d_o = \frac{f_D\ c\ T_{fm}}{2\ B_{fm}}. \tag{1.5}$$

In the intended indoor positioning application, in order for the target (or user's) position to be determined, at least 3 ranging measurements from 3 fixed anchor stations or BSs are needed for triangulation as shown in Figure 1-3. Therefore, this simple primary radar architecture would not be suitable for an indoor environment because beside the problem of multiple radar signal reflections from the walls and obstacles, it would not be possible to determine which user is mapped to which radar signal reflection when all users are totally passive targets. Therefore, a secondary radar architecture is adopted where each user carries a mobile station (MS) which serves as an active target performing ranging measurements with the fixed BSs as will be explained in the next section.