1 Introduction

1.1 Road Safety

Road safety is a major societal issue. While the likelihood of having a road crash for a single individual, on average, is in the range of once every 25 years (in developed countries), society as a whole pays a crushing price for the cumulative effects of crashes [13]. Annually worldwide between 20 to 50 million people suffer non-fatal injuries (with many incurring a disability) and 1.24 million people are killed because of accidents involving motorized vehicles. Road traffic injuries are the leading cause of death among young people, aged 15–29 years. On the roads of the European Union in 2012 28,000 people died, i.e. the equivalent of a medium town, and about 250,000 people were seriously injured [17].

In July 2010 The European Commission has adopted challenging plans to reduce the number of road deaths on Europe's roads to one half by 2020 [16]. There are seven strategic objectives for this end:

1. Improved safety measures for trucks and cars
2. Building safer roads
3. Developing safer vehicles
4. Strengthening licensing and training
5. Better enforcement
6. Targeting injuries
7. A new focus on motorcyclists

Vehicle safety can be loosely separated into 2 categories: passive and active. Passive measures should reduce injury rate when an accident is inevitable. In this category are: seat belts, airbags, anti-lock braking systems (ABS) and electronic stability control (ESC). Active safety means having the ability to predict a situation which could probably result in an accident and having the capability to react to it timely so the accident could be avoided, or at least its' impact is reduced (pre-crash sensing).

Human limitations in sensing and control multiply when hundreds of vehicles share the same roads at the same time. Traffic flow consisting of cars controlled by people is doomed to inefficiency due to human aspects of delayed response to traffic conditions. When we detect brake lights ahead, time is expended as we assess the situation and proceed to apply our own brakes, if needed. When traffic ahead accelerates, a similar lag time is incurred to sense that

Dieses Werk ist copyrightgeschützt und darf in keiner Form vervielfältigt werden noch an Dritte weitergegeben werden.
Es gilt nur für den persönlichen Gebrauch.

condition and follow suit. The aggregate effect of these factors creates “accordion effects” or “shock waves” in dense traffic flows, as well as the relatively slow clearance time for intersections controlled by traffic signals. Traffic congestion is also caused by the sheer volume of vehicles attempting to use roadways, exceeding physical capacity limitations.

Moreover, reducing the time interval from the recognition of the situation to the vehicle’s stop could greatly reduce collision probability. If the reaction time could have been improved by 0.25 s collision probability in case of rear-end collisions reduces by 30 % [35], [26]. Collisions at intersections could have been avoided in 50 % of all cases if the driver knew about the situation 0.5 s in advance. If it is too late to avoid the accident, the information about the location and the severity of the impact lets the vehicle take safety measures such that the risk of injuries is minimized. For example, the detection of an unavoidable side impact gives enough time to inflate airbags [21].

Planning engineers envision a cooperative ecosystem where vehicles exchange data with other vehicles (V2V), between vehicles and the infrastructure (V2I) and between infrastructures (I2I) in real time to have drivers better informed, reducing risks of accidents and making traffic flows run more efficiently and smoothly overall. The human inefficiencies noted above will be gradually moved to the domain of machine sensing and control. From a legal standpoint, sensors and computers are not allowed to make important decisions instead of humans on the highways, but to complement human natural sensors that were not suited for operation while moving at high speeds.

To create such a cooperative ecosystem:

- a system based on fusion of sensors has to be made available
- the costs of these technical solutions have to be brought down so they can be fitted onto mid- to lower-end of the vehicles

1.1.1 Automotive Comfort and Safety Systems

The term “comfort systems” (or “convenience systems”) came into being in the late 90ies when automotive companies were ready to offer driver-assist systems to their customers but were not yet ready to take on the legal implications and performance requirements that would come with introducing a new product labeled as “safety system” [13].

Comfort Systems Overview

- Parking Assist. The simplest form of such system is a rear-facing camera, which simply offers a view of the area behind the vehicle but no driver warnings. Warning capability can be added by an ultrasonic sensor, covering the immediate area around the car. More advanced systems use short range radar to cover an extended range and provide the driver with more precise information as to the location of any obstacle.

Dieses Werk ist copyrightgeschützt und darf in keiner Form vervielfältigt werden noch an Dritte weitergegeben werden.
Es gilt nur für den persönlichen Gebrauch.

- Adaptive Cruise Control (ACC). It is the primary comfort system for highway driving. ACC allows a driver to set a desired speed which is automatically reattained when the road ahead is unobstructed. If a close vehicle in front moves at a slower speed then throttling and brake of the host vehicle is controlled to match this of the slower vehicle. In the future ACC systems will be extended to be operational at low speeds including full-stop capability (also known as "stop-and-go ACC"). Systems currently on the market monitor the scene using either long-range-radar or lidar (laser radar), future systems may also use machine vision.
- Lane-Keeping Assistance (LKA). It uses computer vision technology to detect the lane in which the vehicle is traveling and adds torque to the steering wheel in order that the vehicle stays on the lane.

Safety Systems Overview

Main safety systems can be classified into the following sub-groups [69], [13]:

- Driver Perception Assistance
  - Adaptive headlights: vehicle speed is taken into account to control illumination pattern.
  - Night vision: helps to see objects far behind the view of the vehicle lights; is realised either with passive infrared camera or long range radar.
- Crash Prevention
  - Forward collision warning / mitigation / avoidance. Some European car manufacturers implement only ACC (marketed as a comfort feature), while some Japanese manufacturers added an active brake assist for collision mitigation. Unlike the smooth deceleration of ACC system, the active brake assist provides much higher forces for deceleration. Thus comfort features of ACC are extended by the active brake assist into the safety domain. Systems to prevent forward collisions rely on long range radar or lidar sensing, sometimes augmented by machine vision.
  - Lane departure warning and line change support. Machine vision techniques are used to monitor the lateral position of the vehicle within its lane.
  - Side object warning (or "blind spot monitoring"). A short range radar is used to monitor the rear left/right sectors obscured by the car's carcass.
  - Pedestrian recognition and warning. Sensing systems based on machine vision perform real-time processing to detect the pedestrians and asses the potential danger.
- Pre-crash Sensing. Radar data can be combined with ABS data so if an imminent accident is identified by sensors and/or car dynamics then the brakes are pre-charged, the seat belt are pretensioned, airbags pre-fired, seat orientations will be adapted, sunroof will be closed, etc.

Dieses Werk ist copyrightgeschützt und darf in keiner Form vervielfältigt werden noch an Dritte weitergegeben werden.
Es gilt nur für den persönlichen Gebrauch.

The aforementioned sensor technologies, such as infrared camera, video camera, ultrasound, lidar have each their own specialized advantages [56], [69]. However, radar is the only sensor that:

- can measure both range and angle-of-arrival accurately of both moving and stationary objects
- is capable of directly providing velocity information
- is not affected by weather conditions: it retains its performance in fog/rain/snow
- can be mounted invisibly behind plastic fascia

This suggests radar as the most robust technology for a vehicular environment. Additionally, radar can simultaneously integrate several automotive comfort and safety features.

1.2 Automotive Radar Applications – Brief History and Status

First experiments with automotive radar took place in the late 50ies [91]. Cadillac Cyclone (Fig. 1.1), General Motors' concept car from 1959, was a first car to feature a radar. Behind the shiny black plastic cones (radomes) a modified airplane radar was installed. A proximity warning device was supposed to prevent collisions but it was never tested in practice.

Figure 1.1: Cadillac Cyclone, General Motors, 1959

In the 70ies the development moved to microwave frequencies. From the early beginning the key driver was collision avoidance. Due to progress both in semiconductor microwave sources, such as Gunn diodes and GaAs MMICs and to quickly evolving micro-controllers and DSPs the commercialization of automotive radar became feasible in the 90ies. in 1993 Greyhound (USA) installed more than 1600 Radar collision warning systems in their bus lines [36] yielding a reduction of accidents of 21 % (compared to the year before). The 24.125 GHz pulse-Doppler

Dieses Werk ist copyrightgeschützt und darf in keiner Form vervielfältigt werden noch an Dritte weitergegeben werden.
Es gilt nur für den persönlichen Gebrauch.

radars were developed by Vorad Safety Systems, San Diego and deployed a flat six-by-eight inch phased-array antenna.

In 1999 Daimler introduced 1st commercial radar ACC "Distronic" [109], which operated at 76.5 GHz and used the pulse-Doppler principle. Other automotive manufacturers followed with equipping their top-models with radars.

1.2.1 Automotive Short-, Mid- and Long-Range Radar

Automotive radar is classified according to covered ranges and azimuths (table 1.1). For Short Range Radar (SRR), ranging accuracy and large field of view are more critical than for Long Range Radar (LRR). These are addressed by higher bandwidth, multiple radar placement and antenna design. As explained in chapter 2 the dynamic range of the receiver is very critical in LRR case.

Table 1.1: Classification of Automotive Short-, Mid- and Long-Range Radar [67], [56]

	Detection Range	**Ranging Accuracy**	**Field of View**	**Bandwidth**
	[m]	[m]	[°]	[GHz]
SRR	$0-30$	0.05	$90-180$	$4-5$
MRR	$2-150$	0.1	$30-60$	$0.5-1$
LRR	$20-250$	0.5	$5-20$	$0.2-1$

1.2.2 Automotive Radar Frequency Band Regulation

- 25 – 29 GHz: band allocated in North America for automotive ultra-wide band (UWB) SRR systems
- 22 – 26.65 GHz: allocated by EC (ETSI EN 302 288-1) to be deployed from 2005 till 2013 with penetration rate restricted to 7 % of all cars in each EC country (so that the other services in vicinity of 24 GHz)
- 24.05 – 24.25 GHz: license-free ISM band, can be used for CW radar (since it does not have enough bandwidth for pulsed radar). Since lane change assistance does not require highest range resolution, this band is deployed for MRR applications
- 76 – 77 GHz: this band is standardized in Europe (ETSI EN 301 091) for LRR, is being allocated for Intelligent Transport Services (ITS) in Europe, North America, Japan
- 77 – 81 GHz: EU, Japan, North America allocated this band for UWB SRR and MRR. In EU this band usage was permitted from 2005 onwards

Dieses Werk ist copyrightgeschützt und darf in keiner Form vervielfältigt werden noch an Dritte weitergegeben werden.
Es gilt nur für den persönlichen Gebrauch.

1.2.3 Multi-Channel Automotive Radar Front Ends

Multi-channel front ends are of great interest for current and future applications in vehicular and other fields. The receive channel diversity could be deployed to better exploit the information contained in the received signals for the following purposes:

- Angle-of-arrival estimation is required in LRR. Among other techniques this can be achieved by antenna- and receiver-diversity [95] with conjunction with parameter estimation methods, based on subspace techniques [31], [63].

- The information available from several receive channels could be deployed as an electronic beam former (also known as digital beam former), by steering the beam away from an interferer towards the desired signal. Therefore the immunity to multi-path scattering present in real-world conditions is increased [72], [109]. The electronic beam former is an alternative to mechanically beam steering, which is sensitive in mechanical reliability over lifetime and is limited with regard to miniaturization [91].

- Coherent summation of the multi-receiver outputs improves signal-to-noise ratios thereby improving the equivalent receiver sensitivity.

1.3 Thesis Objectives and Organization

The goal of this dissertation is to present circuit blocks to implement a 77 GHz multi-channel receiver for automotive radar using SiGe technology. The emphasis is put on high linearity and sensitivity of the receiver, for a very high dynamic range is crucial for such instrumental applications.

Beside this:

- development and exploration of alternative design methodologies suitable for designs at the technology margins ($f_{max}/3$)

- minimizing the power consumption by reducing both the circuit blocks' supply voltages and quiescent currents and selecting power-efficient circuit topologies

- integration – reducing of the number of separate chips

The thesis is organized as follows:

In chapter 2 automotive FMCW LRR performance is assessed on system level. Two cases of FMCW radar transceiver combining (quasi-bi-static and mono-static) are compared in presence of several leakages and reflections.

Chapter 3 discusses the circuit environment. Additionally, models are developed for the passivated microstrip transmission line model and for the prober pads.

Dieses Werk ist copyrightgeschützt und darf in keiner Form vervielfältigt werden noch an Dritte weitergegeben werden.
Es gilt nur für den persönlichen Gebrauch.

Chapter 4 focuses on design of active and passive circuits, such as LNA, mixer, several balun types. Various topologies and circuit- and system-level design trade-offs (especially linearity vs. noise) were juxtaposed. The measured circuits are benchmarked with the published results.

Chapter 5 deals with the integration of the circuits from the previous chapter into 1- and 2-channel receivers. For the 2-channel receiver an active LO splitter is designed and isolation improvement techniques are discussed. The measured receivers are benchmarked with the published results.

Chapter 6 wraps up this work with summary, contributions' outline and possible future investigations' suggestions.

Dieses Werk ist copyrightgeschützt und darf in keiner Form vervielfältigt werden noch an Dritte weitergegeben werden.
Es gilt nur für den persönlichen Gebrauch.

Dieses Werk ist copyrightgeschützt und darf in keiner Form vervielfältigt werden noch an Dritte weitergegeben werden.
Es gilt nur für den persönlichen Gebrauch.

2 Automotive LRR FMCW Radar – System Level Approach

2.1 FMCW Radar Fundamentals

2.1.1 Waveform Derivation

Frequency **M**odulated **C**ontinuous **W**ave Radar is a technique for obtaining range information. FMCW Radar has a long history [64], in the past its use was limited to specialized applications, such as radio altimeters. Linear frequency modulation is very versatile when applied to an optimal receiver (also known as correlation receiver) [79] and exists in nature: big brown bat deploys dual linear frequency modulated ultrasonic radar to navigate and forage [48]. In a correlation receiver the transmitted signal is mixed with a delayed replica of itself – this is also known as homodyne receiver. A frequency measurement must be performed to obtain range from FMCW receiver. This is done in the digital domain using FFT (Fast Fourier Transform). The main advantage of FMCW radar is its high time bandwidth product ($T_{\mathrm{sw}}\Delta F$) [23], [41], [94]. High sweep time values improve the overall sensitivity (noise filter bank bandwidth is inverse proportional to sweep time) while the range resolution is inverse proportional to sweep bandwidth.

Frequency modulation can be achieved in several ways. Here one the most common ways is considered – sawtooth modulation of the carrier.
The instantaneous frequency of the transmitted signal is (Fig. 2.1a):

$$f_{\mathrm{TX}} = f_1 + \frac{\Delta F t}{T_{\mathrm{sw}}} \qquad [\mathrm{Hz}] \qquad (0 \le t < T_{\mathrm{sw}}) \tag{2.1}$$

where f_1 is the start frequency (76.5 GHz, in this case), ΔF – the sweep bandwidth of the radar (1 GHz) and T_{sw} is the sweep time duration (typically in the order of magnitude of 1 ms). Therefore, the instantaneous phase of the transmitted signal is:

$$\varphi_{\mathrm{TX}}(t) = 2\pi \int_0^t f_{\mathrm{TX}}(t)\mathrm{d}t = 2\pi f_1 t + 2\pi \frac{\Delta F t^2}{2T_{\mathrm{sw}}} + \varphi_{\mathrm{T}} \qquad [\mathrm{rad}] \qquad (0 \le t < T_{\mathrm{sw}}) \tag{2.2}$$

where φ_{T} is the phase offset due to the integration. The instantaneous phase of the received

Dieses Werk ist copyrightgeschützt und darf in keiner Form vervielfältigt werden noch an Dritte weitergegeben werden.
Es gilt nur für den persönlichen Gebrauch.

signal is:

$$\begin{aligned}\varphi_{\mathrm{RX}}(t) &= \varphi_{\mathrm{TX}}(t-\tau) = 2\pi \int_{0}^{t-\tau} f_{\mathrm{TX}}(t)\mathrm{d}t = \\ &= 2\pi f_1(t-\tau) + 2\pi \frac{\Delta F (t-\tau)^2}{2T_{\mathrm{sw}}} + \varphi_{\mathrm{T}} + \varphi_{\mathrm{R}} \qquad [\mathrm{rad}] \qquad (\tau \le t < \tau + T_{\mathrm{sw}})\end{aligned} \tag{2.3}$$

where φ_{R} is the phase offset added by the target and

$$\tau = 2\frac{d}{c_0} \qquad [\mathrm{s}] \tag{2.4}$$

is the delay of the signal occurring due to two-way propagation (the target is distanced d meters from the radar). As it is apparent from equation 2.4 and previous considerations,

$$\tau \ll T_{\mathrm{sw}} \tag{2.5}$$

After mixing and low-pass filtering the Intermediate Frequency (IF) signal is obtained:

$$\varphi_{\mathrm{IF}}(t) = |\varphi_{\mathrm{RX}} - \varphi_{\mathrm{TX}}| = \left| 2\pi \frac{\Delta F}{T_{\mathrm{sw}}} \tau t + 2\pi f_1 \tau - \varphi_{\mathrm{R}} - \pi \frac{\Delta F \tau^2}{T_{\mathrm{sw}}} \right| \qquad [\mathrm{rad}] \tag{2.6}$$

In equation 2.6, the most important term is the first, since it represents the beat frequency, proportional to the range. The second and third terms in equation 2.6 represent constant phase offset added by target and the last, fourth term can be neglected, since equation 2.5 holds.

$$f_{\text{beat, static}} = \frac{w_{\text{beat, static}}}{2\pi} = \frac{\Delta F}{T_{\mathrm{sw}}}\tau = \frac{\Delta F}{T_{\mathrm{sw}}} 2 \frac{d}{c_0} \qquad [\mathrm{Hz}] \qquad (\text{where } d \text{ is the unknown range}) \tag{2.7}$$

Therefore, equation 2.7 yields $f_{\text{beat, static}} = 33 \ldots 1333$ kHz for $d = 5 \ldots 100$ m.

The beat signal spectrum is:

$$\begin{aligned} S_{\text{beat, static}}(f) &= \int_{0}^{T_{\mathrm{sw}}} \cos(w_{\mathrm{beat}} t) e^{-jwt} \mathrm{d}t = \\ &= \frac{\sin((w_{\mathrm{beat}} - w)\frac{T_{\mathrm{sw}}}{2})}{w_{\mathrm{beat}} - w} \cdot e^{j\frac{w_{\mathrm{beat}} - w}{2} T_{\mathrm{sw}}} + \frac{\sin((w_{\mathrm{beat}} + w)\frac{T_{\mathrm{sw}}}{2})}{w_{\mathrm{beat}} + w} \cdot e^{-j\frac{w_{\mathrm{beat}} + w}{2} T_{\mathrm{sw}}}\end{aligned} \tag{2.8}$$

It must be added that since in time domain the signal is periodic with period T_{sw}, its' Fourier transform is sampled with frequency $1/T_{\mathrm{sw}}$.

This derivation was performed for static targets. For targets moving towards the radar with radial velocity v_{r} [95]:

$$f_{\text{beat, moving}} = f_{\text{beat, static}} - f_{\mathrm{Doppler}} \qquad [\mathrm{Hz}] \tag{2.9}$$

Dieses Werk ist copyrightgeschützt und darf in keiner Form vervielfältigt werden noch an Dritte weitergegeben werden.
Es gilt nur für den persönlichen Gebrauch.