Software Defined Radar

Andreas Stelzer
R. Feger, C. Pfeffer, H. Haderer
Johannes Kepler University (JKU), Linz
a.stelzer@nthfs.jku.at

WS12: EuMIC - SiGe for mm-Wave and THz
Overview

• Introduction - Motivation
  – Radar Principles – Transmit signals
  – Radar Fundamentals – Ambiguity function

• A Software Defined Radar (SDR) Platform
  – Concept – Hardware – Performance
  – Exemplary Implemented Radar Principles:
    • Frequency division MIMO
    • Frequency division MIMO with BPSK und ΔΣ-Mod.
    • Stacked OFDM
    • Phase Coded Continuous Wave (PCCW) MIMO Radar

• Radarbook Evaluation Platform
Motivation I

• State-of-the-art in automotive Radar
  – Linear frequency modulated continuous wave (LFMCW), slow ramp as well as fast chirped

• Pros
  – Deramping in hardware, i.e. even a large transmit bandwidth yields a small IF bandwidth

• Cons
  – Linear ramp generation, analog modulation
Motivation II

• Current discussion for automotive Radar
  – Silicon-Germanium vs. CMOS technology

• CMOS allows for / requires / goes for ...?
  – Higher integration levels – BB and radio?
  – Towards digitally centric designs – VHDL?
  – Alternative modulation schemes – PRN?
  – Integration vs. RF performance – technology node?
  – Automotive market volume high enough – costs?
Pulse Radar

- Localization in “time”
- Time measurement
- Distance measurement
- Range profiles
Short Pulse Train

- Short pulses
- High peak power, difficult for integration
- Receiver variants
  - Fast sampling
  - Sequential Sampling (correlation receiver)
Doppler Radar

- Localization in "frequency"
- Frequency measurement
- Velocity measurement
- Velocity profiles
- Simplest sensor
- Vehicle speed measurement

Spectrogram
Linear FMCW Radar

- Localization in “frequency”
- Localization in “time”
- Range-velocity coupling
- Multiple ramps to resolve range velocity coupling
- “Ghost” targets
- Most widely used
Fast Chirped FMCW Radar

- Dominant localization in “time” per chirp
- Velocity via phase rotation of chirps
- Range velocity processing with 2D FFT
- State-of-the-art for actual/upcoming radars
- Higher IF, higher IF data rate
OFDM Radar

- Orthogonal Sub-carriers
- Instantaneous "FSCW"
- High bandwidth and linear ADC
- Lots of knowledge from communications
- Lots of ongoing research

Spectrogram
CW PRN Coded Radar

- High instantaneous bandwidth (unlimited)
- CW, moderate power
- PRN controlled phase mod.
- Receiver
  - High BW
  - Subsampling
  - Hardware correlators
  - Parallel correlation
- Fully digital, CMOS?
Radar Fundamentals I

- Transmit signal \( s(t) \)
- Amplitude factor, loss, target scattering \( \alpha(t) \)
- Round-trip delay time (RTDT) \( \tau_0 = \frac{2d_0}{c} \)
- Doppler frequency \( \omega_0 = 2\pi f_c \frac{2v_0}{c} \)
- Noise \( n(t) \)
- Receive signal \( r(t) = \alpha(t) s(t - \tau_0) e^{-j\omega_0 t} + n(t) \)
• Correlate receive signal with Doppler shifted transmit signal
\[
c(\tau, \omega) = \int_{-\infty}^{\infty} r^*(t) s(t + \tau) \, dt
\]
\[
c(\tau, \omega) = \int_{-\infty}^{\infty} a(t) s^*(t - \tau_0) e^{j\omega_0 t} s(t + \tau) e^{-j\omega t} \, dt + \text{noise}
\]

• Considering \( \tau_0 = 0, \omega_0 = 0 \) and \( a(t) = 1 \) leads to the Ambiguity Function (AF)
\[
A(\tau, \omega) = \int_{-\infty}^{\infty} s^*(t) s(t + \tau) e^{-j\omega t} \, dt
\]
Typically, short range radars (SRR) work with periodic sequences, thus also the correlation function is periodic, and the calculation of the ambiguity function must be adapted.

Ambiguity Function for periodic sequences with a bunch of sequences for Doppler proc.

\[
A_{\text{seq}}(\tau, \omega) = \int_{-\frac{T_{\text{seq}}}{2}}^{\frac{T_{\text{seq}}}{2}} s_p^*(t) s_p(t + \tau) e^{-j\omega t} \, dt
\]
• Symmetry of the ambiguity function

\[ A(\tau, \omega) = A^*(-\tau, -\omega) \]

• Along the zero-Doppler axis (\(\omega = 0\)) the ambiguity function is the autocorrelation function of the waveform

\[
A(\tau, 0) = \int_{-\frac{T_{seq}}{2}}^{\frac{T_{seq}}{2}} s_p^*(t)s_p(t + \tau) \, dt = R_{ss}(\tau)
\]
• Maximum of ambiguity function

$$|A(\tau, \omega)| \leq |A(0, 0)| = \int_{-\infty}^{\infty} |s(t)|^2 \, dt$$

• Moyal’s Identity

$$\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} |A(\tau, \omega)|^2 \, d\tau \, d\omega = |A(0, 0)|^2$$

⇒ A reduction of the ambiguity function in one place, forces a heightening somewhere else!
Ambiguity Function I

- Linear FMCW Radar (3 ramps)
Ambiguity Function II

- Fast Chirped FMCW Radar
Ambiguity Function III

- OFDM Radar
Ambiguity Function IV

- PCCW with Almost Perfect Autocorrelation Sequence (APAS)
• Development of a Software Defined Radar (SDR) platform for application with 77-GHz SiGe-based multi-channel frontends.

• Technical Data:
  – 4 converter boards with 2 ADCs and 2 DACs, 500 MS/s, 14 bit each.

• Goal
  – Demonstration and verification of concepts and algorithms on real 77-GHz frontend hardware
SDR Evaluation Platform

4x4 Digital transceiver channels
@ 6.125 GBPS

8x DAC channels
14 Bit @ 1000MSPS
update rate
(500 MSPS data rate)

8x ADC channels
14 Bit @ 500 MSPS
data rate

Clock distribution and jitter cleaner

CLKs

Digital IOs

RF frontend supply
3x 2.8-5.5V (⊗3A)

Power supply

RF frontend

User interface

Personal computer

Ext. Ref. CLK

USB 2.0/3.0

SSRAM

SSRAM

FPGA

Stratix GXII

FPGA

Cyclone III

Converter board

DACl

DACQ

ADC

ADCQ

SSRAM

SSRAM
Single Converter Board

- **ADCs**
  - 500 MSPS (Data rate)
  - 14 Bit

- **DACs**
  - 500 MSPS (Data rate)
  - 1 GSPS (Update rate)
  - 14 Bit

- **FPGA**
- **Memory**
RF-Frontends

B7HF200 SiGe:C
Bipolar technology from Infineon
Vcc = 3.3 V
I_{dc} = 131 mA
1428 x 1028 μm²

4TX, 4RX,
7 virtual RX MIMO +
analog TX beamforming

4TX, 4RX,
16 virtual RX MIMO
4 TX and 4 RX channels
Large bandwidth up to 4 GHz (tuned VCO)
  - TDM
  - FDM
  - SOFDM (Stacked OFDM)
Bandwidth up to 400 MHz (SDR with fixed VCO-frequency)
  - TDM
  - FDM
  - OFDM
  - PRN
Performance of ADC/DAC (Calibration ADC)

Interleaved Products

I/Q Imbalances

Relative Magnitude (dB)

Frequency (MHz)
Performance of ADC/DAC (Spurs)

Threshold Level: 60 dB

Threshold Level: 70 dB

Threshold Level: 80 dB
Crest Factor – Time Signals (Golay Phase Values vs. Worst Case)
MIMO Operation (FDM mode, single ramp) and DBF (16 virt. RX antennas) with: \( T_{SW} = 40 \mu s, B_{SW} = 200 \text{ MHz} \)

- \( f_{START} = 10 \text{ MHz} \), \( f_{STOP} = 210 \text{ MHz} \)
- \( f_{START} = 12 \text{ MHz} \), \( f_{STOP} = 212 \text{ MHz} \)
- \( f_{START} = 14 \text{ MHz} \), \( f_{STOP} = 214 \text{ MHz} \)
- \( f_{START} = 16 \text{ MHz} \), \( f_{STOP} = 216 \text{ MHz} \)
Measurements FDM MIMO

Max. unambiguous range: 60 m
Measurement Results – FDMA MIMO

- Digital beamforming result with FDMA MIMO
- No motion compensation required
\(\Delta\Sigma\)-TX FDM MIMO with 6 TX and 8 RX

TX section (6 TX)

RX section (8 RX)

77-GHz VCO

PLL ramp gen.

New RF

New dig.

---

R. Feger, C. Pfeffer, A. Stelzer:
"A Frequency-Division MIMO FMCW Radar System Using Delta-Sigma-Based Modulators"
IEEE MTT-S International Microwave Symposium, 2014, Tampa
ΔΣ-TX FDM MIMO with 6 TX and 8 RX

6 TX 7λ/2-spaced

8 RX λ/2-spaced

RF Frontend

VCO+3 PA

R. Feger, C. Pfeffer, A. Stelzer:
ΔΣ-TX FDM MIMO 6 TX, 8 RX Results
SOFDM – Principle (Receive+DSP)

Extract sub-carriers of each ramp step

|Mag.| Perform range comp.

Combine sub-carrier info. of ramp steps
Measurement Setup
SOFDM 10 steps (BW=2GHz)
SOFDM Range/Doppler Measurements (2 m/s)
Phase-Coded CW Radar

- Perfect code's autocorrelation does not exist for purely binary phase-shift keying!

- Almost perfect autocorrelation sequence (APAS)
Zero Correlation Zone Sequence Sets

H. Haderer, R. Feger, C. Pfeffer, and A. Stelzer,
„Millimeter-Wave Phase-Coded CW MIMO Radar Using Zero-Correlation-Zone Sequence Sets,”
PCCW-MIMO Meas. 4TX, 4RX

H. Haderer, R. Feger, C. Pfeffer, and A. Stelzer,
„Millimeter-Wave Phase-Coded CW MIMO Radar Using Zero-Correlation-Zone Sequence Sets,“
• SDR platform for complex scenarios and modulation.
• Radarbook for simple testing
  – Evaluation platform for research, development and teaching.
• Out-of-the-box measurements of Doppler, FMCW, MIMO, Range-Doppler
• Example Tracking of a UAV (offline)
UAV Tracking with Radarbook
Conclusion

• SDR Platform allows development of novel modulation schemes with real measurements
• (L)FMCW and (PRN) PCCW radar behave similar under similar assumptions
• Digital centric sensor design can be largely shifted towards VHDL based hardware design
• With CMOS the radar principle must be reassessed with respect to more digitally oriented approaches
• Technology node is also a question of topology, high RF-performance vs. high-digital performance
Acknowledgment

• Institute for Communications Engineering and RF-Systems
• Johannes Kepler University Linz
• Danube Integrated Circuit Engineering
• Infineon Technologies AG
• Linz Center of Mechatronics