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MOre Safety for All by Radar Interference Mitigation

D1.5 – Study on the state-of-the-art interference mitigation techniques

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MOSARIM

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SEVENTH FRAMEWORK PROGRAMME

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Revision chart and history log

Version	Date	Reason
0.1	30.04.2010	Initial version by Martin Kunert
0.11	14.05.2010	Inputs from AC
0.2	14.05.2010	Inputs from DAI and HKG
0.3	19.05.2010	Consolidation of all inputs (M. Kunert)
0.4	21.05.2010	Inputs from VIC and RB
0.5	26.05.2010	Input from HKG
0.6	27.05.2010	Input from ADC
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0.7	31.05.2010	Input from KIT-U
0.8	10.06.2010	Input from HKG on PREF06,CREF11,CREF12
0.9	10.06.2010	Input from AC on CREF17, CREF18, CREF20
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1.1	14.06.2010	Version for Peer Review
1.2	17.06.2010	Reviewed by HKG
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1.4	23.06.2010	Reviewed by HKG
1.5	28.06.2010	Reviewed by VIC
1.6	28.06.2010	Final version for submission

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1 Introduction

The topic of possible interference is inherent to all wireless applications sharing the same or an overlapping frequency range. Also automotive radars are exposed to various emissions from other frequency users such as automotive radars in others cars at low distance, other radars roadside or near roads such as speed radars, radars for surveillance purposes e.g. such as surveillance of rail-road crossings or surveillance of buildings. The characteristics of these transmitters is within the limits of ETSI standards or country specific standards in most cases, may however be much higher in some cases especially in cases of governmental use.

Because of that inherence, already in the past techniques to mitigate interference between different or even same devices were investigated. Obvious techniques to reduce interference risk are:

- transmitters use low power or a low duty cycle, a narrow bandwidth and a narrow beam width
- receivers have a low bandwidth and a narrow beam width.

But these properties are normally in contradiction with requirements for optimum application performance, so that more sophisticated mitigation techniques are desired.

Section 2 gives a summary of such more sophisticated state-of-the-art techniques and section 3 a short description of respective references that were found in a patent and conference paper survey.

The established patent and paper database regarding interference mitigation techniques for radio-location applications will be used within the MOSARIM research project as a starting point to investigate and elaborate further mitigation techniques for automotive radar applications.

2 Basic interference mitigation techniques

Based on the results of the patent and conference paper survey conducted, the different mitigation techniques are classified in six different basic techniques that are described in their principle operation modes in the following sections. The different basic techniques can also be combined to further reduce the probability of a radar-malfunction.

2.1 Interference mitigation in the polarization domain

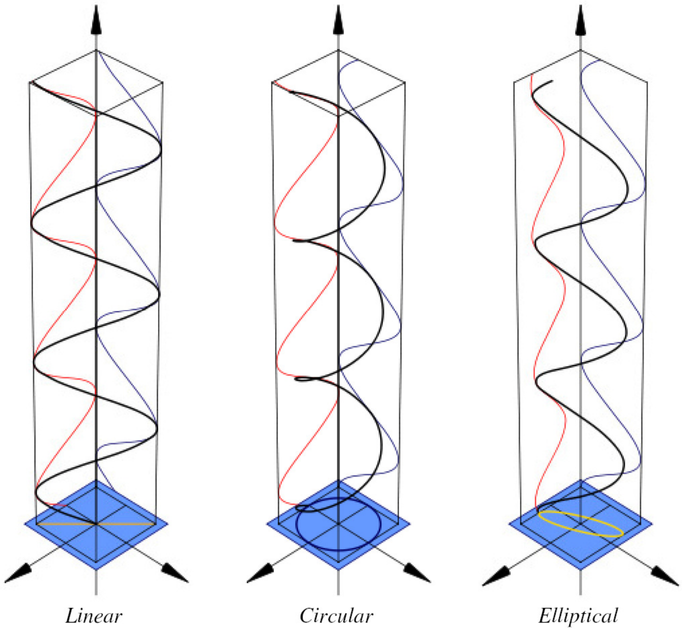
Electromagnetic waves exhibit polarization that is a property describing the orientation of their oscillations. Depending on the phase and amplitude of the complex electromagnetic vector one can differentiate between the following three polarization states:

a) linear polarization: The two orthogonal components of the electromagnetic vector are in phase with same amplitude

b) circular polarization: The two orthogonal components of the electromagnetic vector have the same amplitude and are exactly 90 degrees out of phase

c) elliptical polarization: The two orthogonal components of the electromagnetic vector are not in phase and have either not the same amplitude or are not exactly 90 degrees out of phase

These three polarization states are graphically shown in the right Figure. For circular and elliptical polarization the rotation of the electromagnetic field vector depends on the relationship between the two phases and turns either clockwise (left hand circular) or counter-clockwise (right hand circular).



Depending on what kind of polarization is used the wave generation principle and the used antenna types may vary. Almost all automotive radar devices use the linear polarization. The orientation of the electric field vector, however, differs from radar device to radar device and is often either horizontally or vertically oriented.
While for circular and elliptical polarization a decoupling or interference mitigation effect by choosing a specific circular or elliptical polarization is not possible, this can be well done with linear polarization. (Remark: Reflection or scattering on objects may alter the polarization direction of linear polarized electromagnetic waves).
The decoupling effect that can be attained by changing the polarization direction of a dish antenna is shown in Figure 2.1.1.

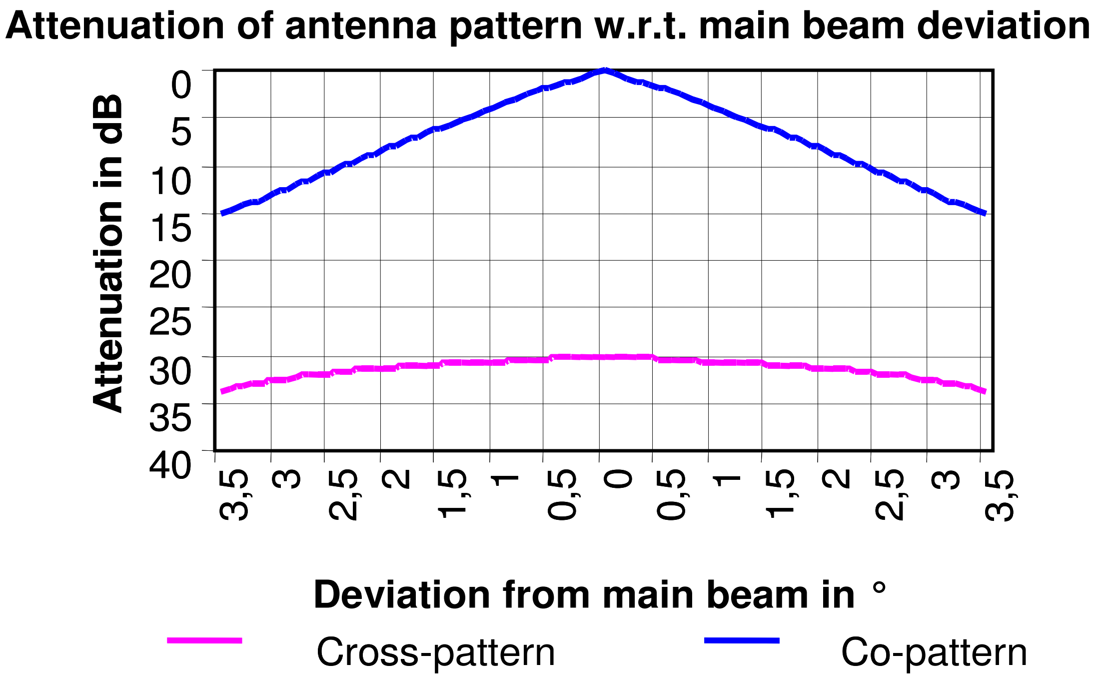


Figure 2.1.1: Co- and Cross polar pattern of a dish antenna

It can be concluded that by using 90 degree between the polarization direction of the interferer antenna and the victim antenna a decoupling of typically more than 20 dB can be achieved. The decoupling effect depends on the specific antenna parameters.

Remark: Only the direct LOS (Line of Sight) propagation is taken into account and multipath reflection or reflection at nearby obstacles are neglected. Reflections on ground surface and other obstacles may turn the polarization of the transmitted electromagnetic wave. So the true cross-polarization interference mitigation effect may be reduced in the presence of obstacle reflection.

Conclusion:
By using cross-polarized orientation between the victim and interferer antenna the interference effects can be mitigated in the order of 20 dB ±10 dB.

2.2 Interference mitigation in the time domain

To measure the distance to target objects, radar sensors usually apply a time domain modulation of the radar transmit frequency. With the same time dependency, normally the centre frequency of the receiver bandwidth is modulated. Interference now occurs if an interferer transmission frequency accidentally hits the victim receiver bandwidth.

To mitigate interference effects, the following time domain approaches are feasible:

- Use an as low as possible transmit duty cycle in order to reduce the probability of hitting a victim receiver bandwidth
- Use an as short as possible receiver measuring time in order to reduce the probability of being hit by an interferer transmitter
- Use a random timing of the used time domain modulation of transmit frequency (for example vary a pause length before a next FMCW chirp starts or vary a FMCW slope) in order to avoid periodic interferences

2.3 Interference mitigation in the frequency domain

Interference mitigation techniques in the frequency domain consist of measures which avoid that other radars transmit in the reception bandwidth of a given radar. To achieve this, the reception bandwidth of the victim radar and/or the transmission bandwidths of the interfering radars need to be shifted in order to separate them in the frequency domain. That is achieved by introducing sub-bands as shown in Fig. 2.3.1. This makes sense when all radars have the same reception bandwidth that covers only parts of the designated frequency range defined by the frequency authorities.

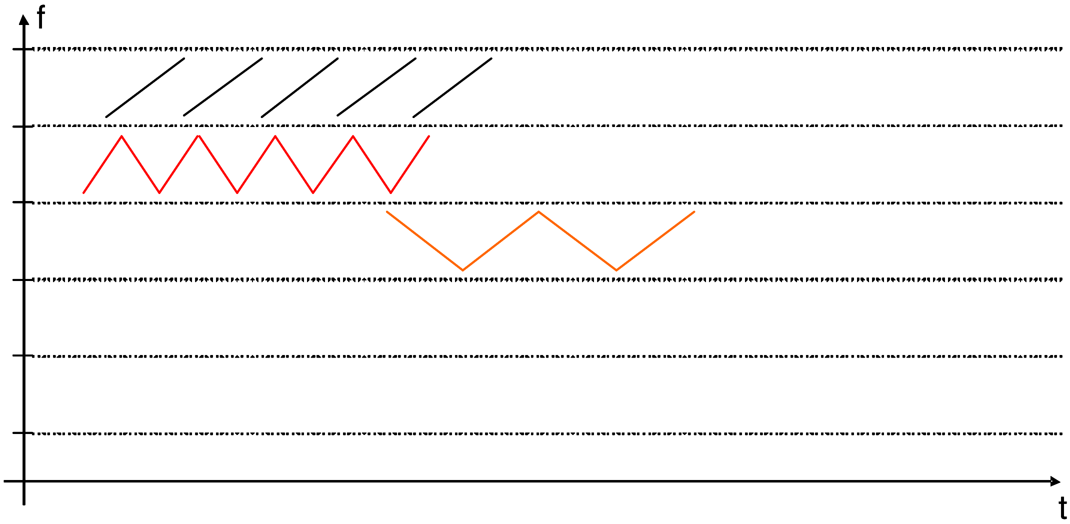


Fig. 2.3.1: Division of a frequency band into five sub-bands. The shown three radars have the same transmission and reception bandwidth

2.4 Interference mitigation in the coding domain

For the study of work package 1.5 coding techniques will be considered mostly in their role as enablers for multiple access to a common resource. Specifically, in automotive radar systems (Adaptive Cruise Control or Short Range Radars) the shared resource is the frequency band allocated for radar operation. In this context, coding refers to a technique using a device specific code for the radar waveform modulation. The same code is used in the demodulation stage, allowing each user (device) to recover the measurement data corresponding to its code. Codes for multiple access must satisfy to orthogonality relations, in order to minimize the crosstalk between different users.

The description of coding above is more specific than the definition used in the field of telecommunications, where coding refers to various techniques used to adapt the information rate to the channel used for transmission. In this context the adaption does not necessarily focus on perturbations by other users, but also on improvements to bit error rates in noisy channel situations. Nevertheless, coding techniques used in telecommunications systems can serve as a source of inspiration for multiple access radar systems. This field is generally referred to as CDMA (for Code Division Multiple Access). [OR98].

2.4.1 Variations on the CDMA approach

The CDMA approach can have multiple expressions, as illustrated schematically in Fig. 2.4.1.1.

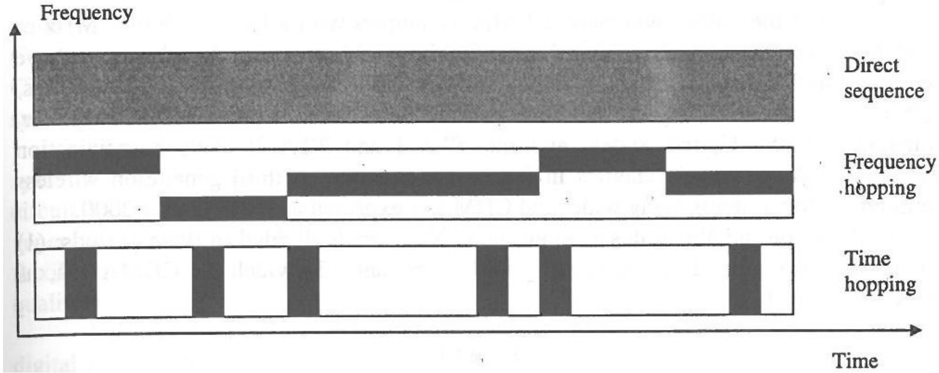


Figure 2.4.1.1 - Schematic representation of 3 approaches to CDMA Excerpt from [OR98]

- Direct-sequence (DS-) CDMA implies a direct coding of the bit stream transmitted by the emitter. This technique is used is used for example in GPS and Galileo navigation devices, as well in Wi-Fi systems (IEEE802.11b). It is also referred to as DSSS (Direct Sequence Spread Spectrum).
- In frequency-hopping spread spectrum (FHSS), the code is used to determine the width of frequency jumps which are performed at a constant repetition rate. This technique requires frequency agile modulation and demodulation. It is used for example in the Bluetooth protocol.
- In time-hopping spread spectrum, the amplitude of the transmitted signal is modulated in time intervals given by the code.
- In multiple-carrier (MC-) CDMA (not illustrated), each user is allowed to transmit simultaneously on multiple subcarriers, the frequency spacing between the subcarriers being given by the code. The orthogonal frequency division multiple access (OFDMA) approach can be considered as a specific case of MC-CDMA. It is used in the IEEE802.16 WiMax standard.

In Annex A a more detailed study and overview of the different coding techniques is provided.

2.5 Interference mitigation in the space domain

For applications where a certain azimuth or elevation range is covered, a mechanically or electronically scanned beam can be used to reduce interference risk. Furthermore, interference risk can be mitigated by choosing the scanned azimuth or elevation range adaptive to the current environment to be just as small as necessary for the current application.

2.6 Interference mitigation by strategic approaches

Using additional hardware and/or software, mitigation can be achieved in the following more sophisticated ways:

Communicate and avoid	With the availability of inter-vehicle communication, timing and/or frequency bands could be negotiated to avoid that radars transmit at the same time in the reception bandwidth of other radars.
Detect and avoid	Some ways of interference can be detected in the time domain (see for example peak in Fig. 2.6.1) or in the frequency domain and the used timing or frequency bands changed (see example in Fig. 2.6.2). In the space domain, interference from a certain azimuth angle can be avoided by leaving out just that azimuth angle during a scan.
Detect and repair	As before, but after interference is detected, in some cases it is possible to repair the disturbance or lower it by adapting detector thresholds. In Fig. 2.6.1 for example, the peak can be eliminated using a Median filter.
Detect and omit	As before, but after interference is detected, the interfered measurement results are not used for further processing.
Listen before talk	Only start to transmit if no other device is sensed to be active

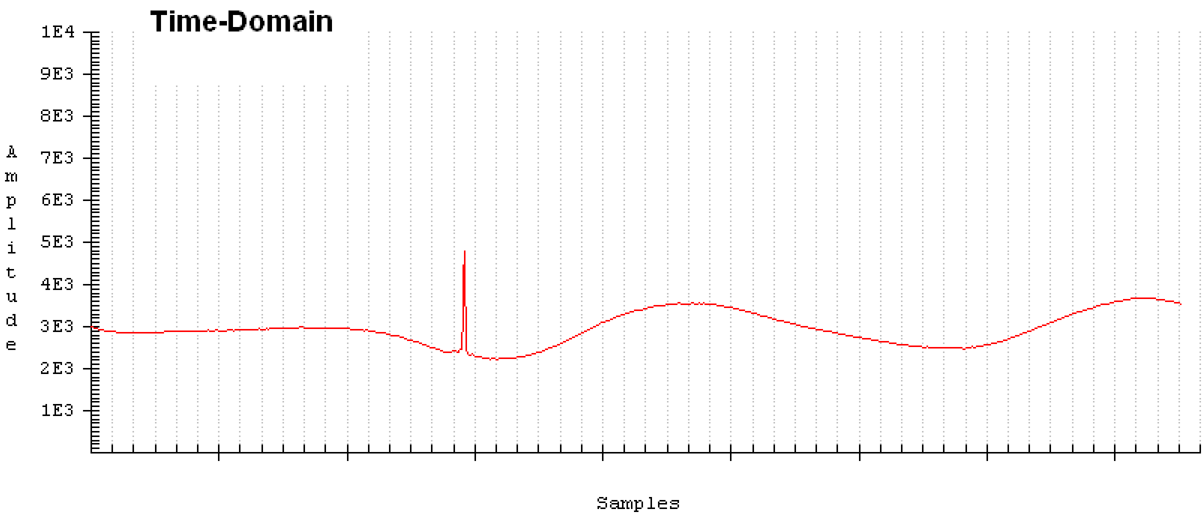


Fig. 2.6.1: Example of received time domain signal with single peak-shaped interference

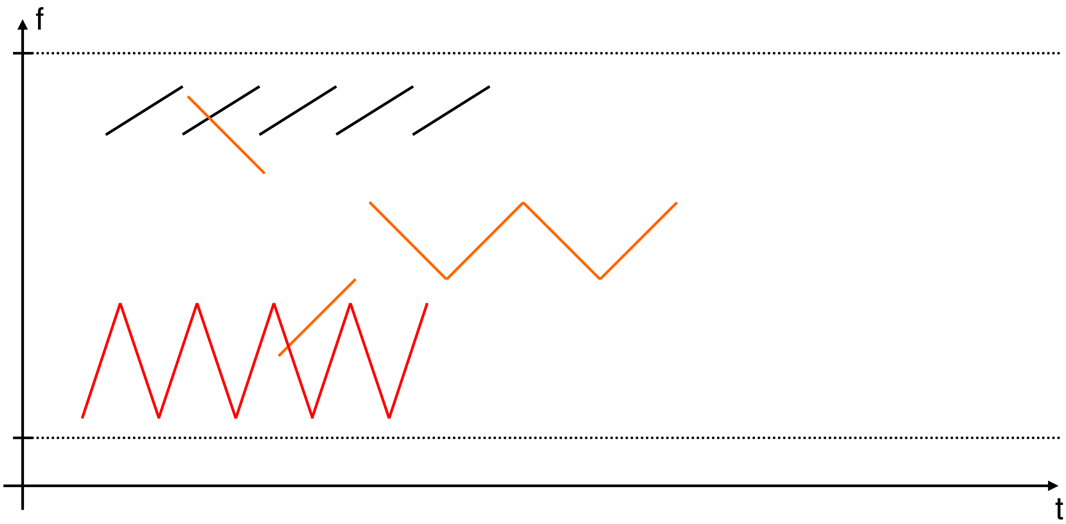


Fig. 2.6.2: Three radars share a frequency band while the orange one chose its frequency range after interference was detected with other radars.

3 Survey database overview

In this chapter, the patents and conference papers that are collected in an interference mitigation technique database on the MOSARIM web-server are described in a short form to provide the reader with the basic idea and principle of the mitigation effects. Based on this information the reader can decide whether to read the complete document in the database or to skip it.

An overview of the patents is given in Table 3.1 and of the conference papers in Table 3.2. .

Section	Short form	Title	Basic technique(s)	Expected interference mitigation effect
3.1.1	PREF01	Method of preventing interference between radars and radar system having interference preventing function	Communicate and avoid (time domain)	high
3.1.2	PREF02	Radar sensor having a CFAR detector	Time domain	high
3.1.3	PREF03	Radar apparatus and radar system for a vehicle	Detect and avoid (various domains)	depends
3.1.4	PREF04	Automotive radar with composite multi-slope FM chirp waveform	Frequency domain, time domain	t.b.d.
3.1.5	PREF05	Fourier-transform-based radio interference mitigation	n/a	low (~20 dB)
3.1.6	PREF06	Doppler radar	Detect and avoid (frequency domain)	t.b.d.
3.1.7	PREF07	Frequency-phase coding device	Coding domain	t.b.d.
3.1.8	PREF08	System and method for reducing a radar interference signal	Detect and repair (time domain)	medium (~40 dB)
3.1.9	PREF09	Pulse Doppler radar interference reduction method for vehicle anti-collision or building security system	Coding domain	low (~15 dB)
3.1.10	PREF10	Interference determination method and FMCW radar using the same	Detect and repair (time domain)	t.b.d.
3.1.11	PREF11	Interference avoidance system for vehicular radar system	Detect and avoid (frequency domain)	t.b.d.
3.1.12	PREF12	Vehicular distance-warning radar	Polarization domain	low (10 to 30 dB)
3.1.13	PREF13	Radar system for detecting surroundings with compensation of interfering signals	Time and frequency domain	low (~20 dB)
3.1.14	PREF14	Method for the suppression of disturbances in systems for detecting objects	Time domain	low (~20 dB)
3.1.15	PREF15	Automotive radar system with anti-interference means	Detect and avoid, communicate and avoid (frequency domain)	high
3.1.16	PREF16	Interference rejection method for an automotive radar CW/ICC system	Detect and repair (time domain)	high
3.1.17	PREF17	Procedure for the elimination of interference in a radar unit of the FMCW type	Detect and repair (time domain)	high
3.1.18	PREF18	FMCW radar device and method for detecting interference	Detect and avoid (polarization and frequency domain)	t.b.d.
3.1.19	PREF19	Adding error correction and coding to a radar system	Coding domain	depends
3.1.20	PREF20	Method for operation of a radar device	Detect and avoid (frequency domain)	high
3.1.21	PREF21	Bridge detecting and false alarm suppressing method for motor vehicle, involves …	Coding domain	medium
3.1.22	PREF22	Radar device and methods for suppression of disturbance of a radar device	Time domain	low (~10 dB)

Table 3.1: Patent reference list overview

Section	Short form	Title	Basic techniques	Expected interference mitigation effect
3.2.1	CREF01	Reduction of Interference in automotive radars using multiscale wavelet transform	Detect and omit (time domain)	t.b.d.
3.2.2	CREF02	Reduction of interference in microwave automotive radars	Coding domain	ca. 5dB
3.2.3	CREF03	Research on key technologies for collision avoidance automotive radar	Frequency domain and time domain	t.b.d.
3.2.4	CREF04	SS-FH signals used for very low interference in vehicular cruising control systems	Frequency domain and coding domain	t.b.d.
3.2.5	CREF05	Time-varying interference suppression in communication systems using time-frequency signal transforms	Detect and repair (frequency domain)	t.b.d.
3.2.6	CREF06	Wavelet-domain communication system (WDCS) interference avoidance capability: analytic, modelling and simulations results	Time domain and frequency domain	6 – 12dB
3.2.7	CREF07	Novel pulse-sequences design enables multi-user collision avoidance vehicular radar	Time domain	ca. 10dB
3.2.8	CREF08	A novel transmit signal based on high range resolution concept for FLAR or AICC system applications	Coding domain	Depends on code length
3.2.9	CREF09	Agile digital detector for RFI mitigation	Only interference detection (frequency domain)	t.b.d.
3.2.10	CREF10	Adaptive reduced-rank interference suppression based on multi-stage Wiener filter	Coding domain	t.b.d.
3.2.11	CREF11	Airborne radar interference suppression using adaptive three-dimension technique	Space and time domain	t.b.d.
3.2.12	CREF12	Combining raised cosine windowing and per tone equalisation for RFI mitigation in DMT receivers	Frequency domain	t.b.d.
3.2.13	CREF13	OFDM as a possible modulation technique for multimedia applications in the range of mm waves	Coding domain	ca. 11dB for impulse noise
3.2.14	CREF14	Listen before talk technique	Listen before talk	Depends on sensor density
3.2.15	CREF15	Detect and avoid technology	Detect and avoid (frequency domain)	Depends on available bandwidth
3.2.16	CREF16	A real time signal processing for an anti-collision road radar system	Coding domain	t.b.d.
3.2.17	CREF17	Hardware/software exploration for an anti-collision radar system	Coding domain	5 – 10dB
3.2.18	CREF18	Conceptual design of a dual-use radar/communication system based on OFDM	Coding domain	t.b.d.
3.2.19	CREF19	Mutual interference of millimeter-wave radar systems	Time domain and space domain	10 – 30dB
3.2.20	CREF20	SiGe circuits for spread spectrum	Coding domain	t.b.d.

Section	Short form	Title	Basic techniques	Expected interference mitigation effect
		automotive radar		
3.2.21	CREF21	Design and demonstration of an interference suppressing microwave radiometer	Detect and repair (time domain, frequency domain)	Dependent on observing time

Table 3.2: Conference paper reference list overview

3.1 Patent survey database

3.1.1 PREF01 – Method of preventing interference between radars and radar system having interference preventing function

Abstract:

In this patent the inventor proposes to use time multiplexing for two or more radars mounted on an automotive vehicle for detecting object. The first radar is detecting object in front of the vehicle and the second radar is detecting object behind the vehicle or both radars are positioned close to each other. Proposed is to choose the transmission times for both radars X1 and X2 with cycle transmission periods T1 and T2 to satisfy the formula: $K \cdot T2+X2+X1 \leq T1 \leq (K+1) \cdot T2-X2-X1$, with $T1>T2>X1+X2$ and K a positive integer. The sensors are synchronized with transmission times and duration of the transmitted signals. For two vehicles, in which the periods T1 and T2 and transmission times X1 and X2 are set to satisfy the above formula, the interference between the two radars on different vehicles according does not occur continuously more than two times. A single interference is detected and replaced with an estimation based on a history of previous received data. The invention prevents the interference between radars without using additional devices in radar system.

Patent reference in Bibliography	PREF01
Restriction to a specific radar type	Radar system with period T1, T2, and transmission times X1, X2
Implementation effort	low
Side-effect with other methods	Nothing expected
Mitigation effect on TX path	yes (time domain)
Mitigation effect on RX path	yes (detection, estimation)
Computational effort	low
Interference mitigation category	Communicate and avoid (time domain)
Harmonization needed	yes
MOSARIM relevant	Yes, but not applicable in scenarios with high density of traffic and multiple radar transmitters/receivers
Range of mitigation effect	For sensor on single vehicle interference can be completely eliminated

3.1.2 PREF02 – Radar sensor having a CFAR detector

Abstract:
In this patent the inventor proposes to operate radar sensor with a randomized pulse repetition frequency (PRF), which randomizes detected RF interference while maintaining echo signal coherence. The invention relates to short-range pulse-radar with constant false alarm rate (CFAR) detector. The PRF generator is modulated by the noise generator. The range gate timing relative to an echo return is not affected by the randomized PRF, the RF interference is however randomly sampled. This results in broader spectral width of the interference signal than the desired radar signal allowing filters to separate the receive signal into signal channel and in interference channel with help of signal filter and interference filter. After signal and interference envelope detector the output of both channels is given on CFAR detector. The output of the interference provides o reference level for a CFAR threshold detector, so the radar sensor does not give false triggers due to RF interference.

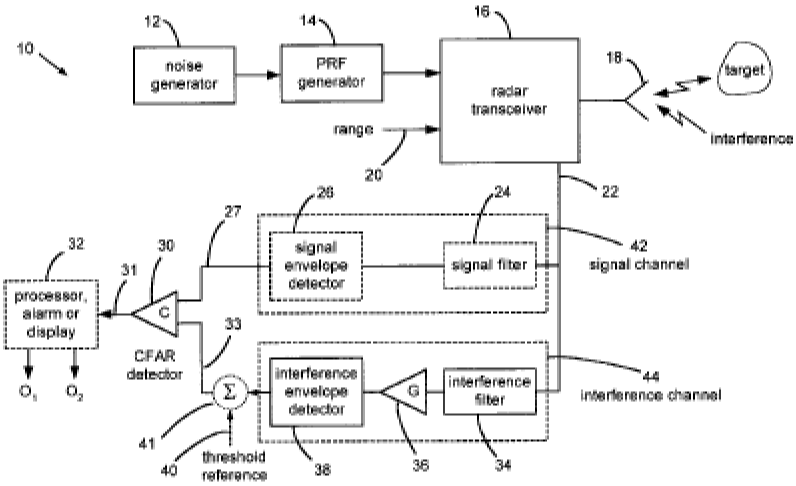


Fig. 3.1.2.1 Block diagram of a radar receiver

Patent reference in Bibliography	PREF02
Restriction to a specific radar type	Short-range pulse-radar with CFAR
Implementation effort	Medium, implementation in hardware and processing
Side-effect with other methods	Nothing expected
Mitigation effect on TX path	no
Mitigation effect on RX path	yes
Computational effort	Medium
Interference mitigation category	Time domain
Harmonization needed	no
MOSARIM relevant	yes
Range of mitigation effect	Theoretically no false detection

3.1.3 PREF03 – Radar apparatus and radar system for a vehicle

Abstract:
In this patent the inventor proposes to operate radar system for automotive with multiple sensors on a single vehicle. The system includes interference detector which determines the presence or absence of the interference on the basis of the received wave. Each of the radar sensors in the system can take one of the modulation states. Modulation states differ with carrier frequency, modulation type, orientation of polarization plane of the wave, transmission

cycle, and/or modulation code. When the interference detector detects interference the modulation state selector selects randomly a new modulation state for the radar sensor. The interference can be avoided by communication of used modulation states. Communication between radar sensors in the same vehicle can be carried out by CAN communication, communication with other vehicles can be carried out by inter-vehicle communication or by road-vehicle communication. Proposed is also a priority identification codes. This method ensures that the radar sensor having the higher priority can operate without interference.

Patent reference in Bibliography	PREF03
Restriction to a specific radar type	no
Implementation effort	High: detection of interference, various modulation stated, communication between sensors
Side-effect with other methods	Nothing expected
Mitigation effect on TX path	yes
Mitigation effect on RX path	yes
Computational effort	moderate
Interference mitigation category	Detect and avoid (various domains)
Harmonization needed	yes
MOSARIM relevant	yes
Range of mitigation effect	Depending on used modulation states

3.1.4 PREF04 – Automotive radar with composite multi-slope FM chirp waveform

Abstract:
In this patent the inventor proposes using a multi-slope FM chirp waveform in dense-signal multiuser environment. The slopes of the chirp signals are normalized to the mean slope and the duration time is the same of all transmitted chirps. The slopes of the chirp signals are optimal chosen as chirp pair with opposite slopes or four chirps with opposite as well as inverse slopes. With chirp quadruples and chirp doublets other configuration of the transmit signals can be constructed. A burst of chirps is transmitted where the time gap between two bursts can vary in some regular or irregular fashion. In the burst separate chirps are selected in a random order. Form the received radar signal the range and the velocity of the object are estimated using all beat frequencies form all chirp signal. In practical applications low or moderate interference level can be tolerated with some performance degradation. In case of catastrophic interference at one of the received chirps signal an algorithm which excludes a pair of chirps with opposite or inverse slopes. The estimation of the range and velocity of the objects is calculated for all cases with one pair (or two pairs) excluded. With only one catastrophic interference achieved result is a cluster with incorrect estimation and an isolated point appearing outside the main cluster. With suitable classification the correct range and velocity estimate can be determined.

Patent reference in Bibliography	PREF04
Restriction to a specific radar type	FMCW
Implementation effort	Moderate
Side-effect with other methods	Nothing expected
Mitigation effect on TX path	yes
Mitigation effect on RX path	yes
Computational effort	moderate
Interference mitigation category	Frequency domain and time domain
Harmonization needed	no

MOSARIM relevant	yes
Range of mitigation effect	t.b.d.

3.1.5 PREF05 – Fourier-transform-based adaptive radio interference mitigation

Abstract:
In this patent the inventor proposes an adaptive noise cancelation technique for Radio Frequency interference (RFI) mitigation applicable in Synthetic Aperture Radar (SAR) image processing. Proposed interference cancelation uses for the RFI rejection pre-nadir data, which are data recorded before the radar nadir returns and post-nadir data. Assumed is the post-nadir data are superposition of a signal which is either target or clutter and noise interference component, and the pre-nadir data is taken as observation of the interference. An optimal signal estimate can be obtained through subtraction of the interference estimate from the post-nadir data. The interference estimate is calculated from pre-nadir and post-nadir data. This approach can be used for suppression of the 'stationary' RFI. The FOPEN III receivers have problems with unbalanced I- and Q-channels and timing errors. Proposed in this patent algorithm initially removes separately the average range bias of the I- and Q-channel. Next both channels are equalized by properly compensating their phase difference and gain imbalance due to either constant or random timing jitter. Following the I/Q equalization, adaptive RFI rejection is performed.

Patent reference in Bibliography	PREF05
Restriction to a specific radar type	SAR, pre- and post-nadir data, IQ-demodulation
Implementation effort	Moderate, if pre- and post-nadir is recorded
Side-effect with other methods	Nothing expected
Mitigation effect on TX path	no
Mitigation effect on RX path	yes
Computational effort	Moderate, rejection of the RFI in signal processing
Interference mitigation category	n/a
Harmonization needed	no
MOSARIM relevant	no
Range of mitigation effect	~20dB

3.1.6 PREF06 – Doppler Radar

Abstract:
In this patent the inventor proposes to detect interference in a certain frequency range above the system IF frequency range by using a respective band pass filter. If interference occurs, the transmit frequency is automatically changed to avoid the interference.

Patent reference in Bibliography	PREF06
Restriction to a specific radar type	CW Doppler radar
Implementation effort	Moderate
Side-effect with other methods	Nothing expected
Mitigation effect on TX path	yes
Mitigation effect on RX path	no
Computational effort	low
Interference mitigation category	Detect and avoid (frequency domain)

Harmonization needed	no
MOSARIM relevant	yes (general approach: detect and avoid)
Range of mitigation effect	t.b.d.

3.1.7 PREF07 – Frequency-phase coding device

Abstract:
In this patent the inventor proposes a Doppler-tolerant pulse-compression code generator. Approximately orthogonal codes will prevent radar interference and suppress jamming. Codes are generated by phase-coding the frequency-band steps and also altering the time-sequence of the frequency steps of a step-approximation to a linear FM chirp pulse. Wide-band radars have smaller range cells, less clutter from rain or chaff and are more difficult to jam because of increased thermal noise power due to the wider bandwidth at the radar receiver.
To permit many wide band radars to share the same spectral space without mutual interference, multiple sets of uncorrelated codes are required. Unfortunately the known coding techniques, e. g. pseudorandom phase coding, are intolerant to Doppler shift. The most Doppler tolerant pulse coding sequence is linear FM or step approximation to linear FM pulse coding.

Patent reference in Bibliography	PREF07
Restriction to a specific radar type	FM or FSK wideband radar systems
Implementation effort	medium
Side-effect with other methods	Nothing indicated
Mitigation effect on TX path	yes
Mitigation effect on RX path	yes
Computational effort	medium
Interference mitigation category	Coding domain
Harmonization needed	t.b.d.
MOSARIM relevant	probably
Range of mitigation effect	t.b.d.

3.1.8 PREF08 – System and method for reducing a radar interference signal

This interference mitigation method uses the comparison of signal-slopes with threshold values to determine, whether interference is present or not. The method was applied again for a FMCW radar system. The principle of the complete radar system is shown in Figure (3.1.8.1). If no interference is detected, signal (76) is directly processed by the radar return signal processor. If interference is detected, the interference is found and removed and then handed over to the radar return signal processor.

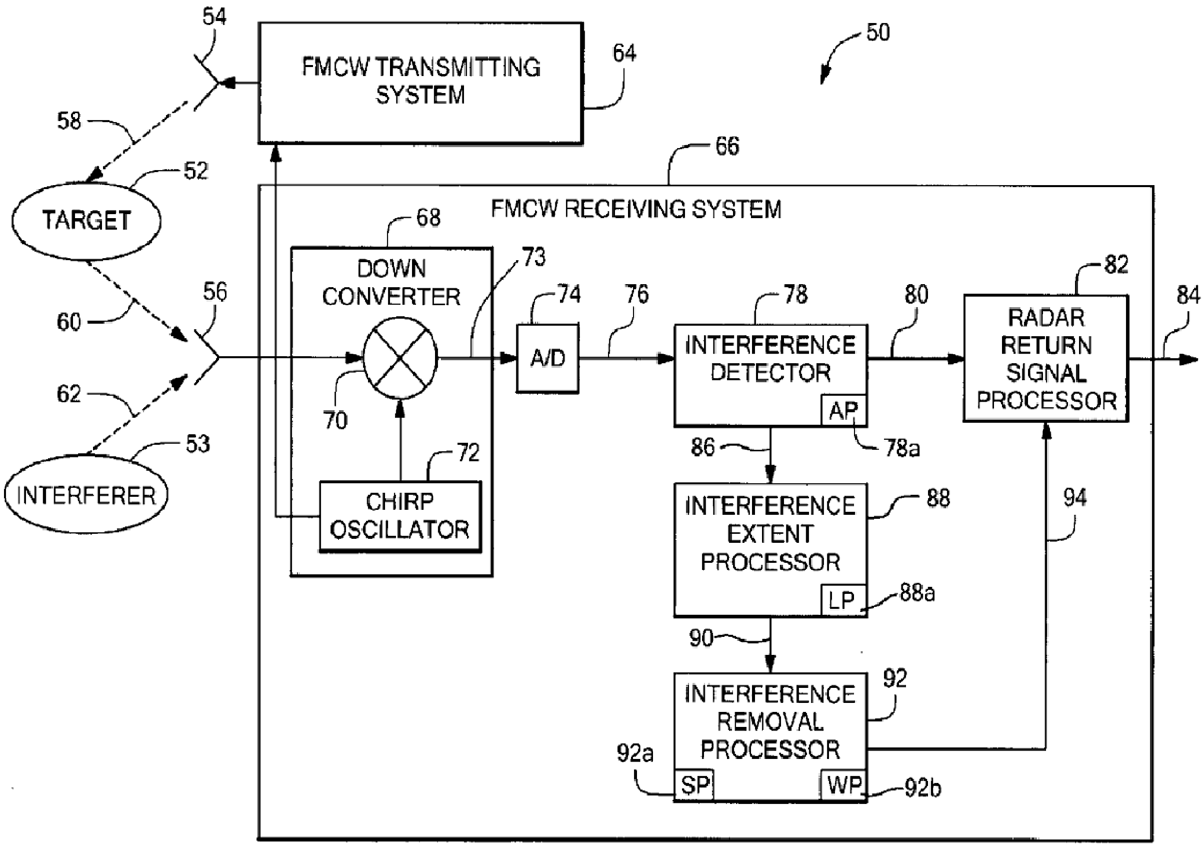


Figure 3.1.8.1: Complete radar system principle

After the A/D-conversion (74), the signal is scanned for interference by the interference detector (78). Within the interference detector, the slope is calculated by the formula

$$slope(j) = |time\ sample(j+1) - time\ sample(j)|$$

for j=1:N-1, where j is the array index that indicates a change in time with the sample time Δt. Thresholds for comparisons are created out of look up tables or formulas, which are based on inside knowledge and are not described in full detail within this patent. However, the principle of the interference detector is the following:

Figure (3.1.8.2) shows two graphs. The lower one represents the digitalized analog signal at point (76) in Figure (3.1.8.1). Out of this digitalized signal, the interference detector (Figure (3.1.8.1), box 78) creates the slope over time (Figure (3.1.8.2), upper graph). The interference detector indicates interference if the slope of the received signal exceeds thresholds like 122 and 124 for a not in detailed specified number of samples (here, 122 is a threshold based on a slope maximum, 124 is a threshold based on a mean slope value). If interference is indicated, the zone of interference is marked. In Figure (3.1.8.2), upper graph, the zone of interference begins at 130 and ends at 132. Now, the interference extent processor inserts so called “guard bands”, which should help avoiding relevant discontinuities. The guard bands do not more than extending the zone of interference by moving indices before and after the threshold exceeding points. In the lower graph in figure (3.1.8.2), the extended zone of interference is placed between (160a) and (160b). The last step of this interference mitigation method is done by the interference removal processor, which zero pads the zone of interference or replaces it by mean slope values, or something like that. The authors used zero padding and presented their results in Figure (3.1.8.3).

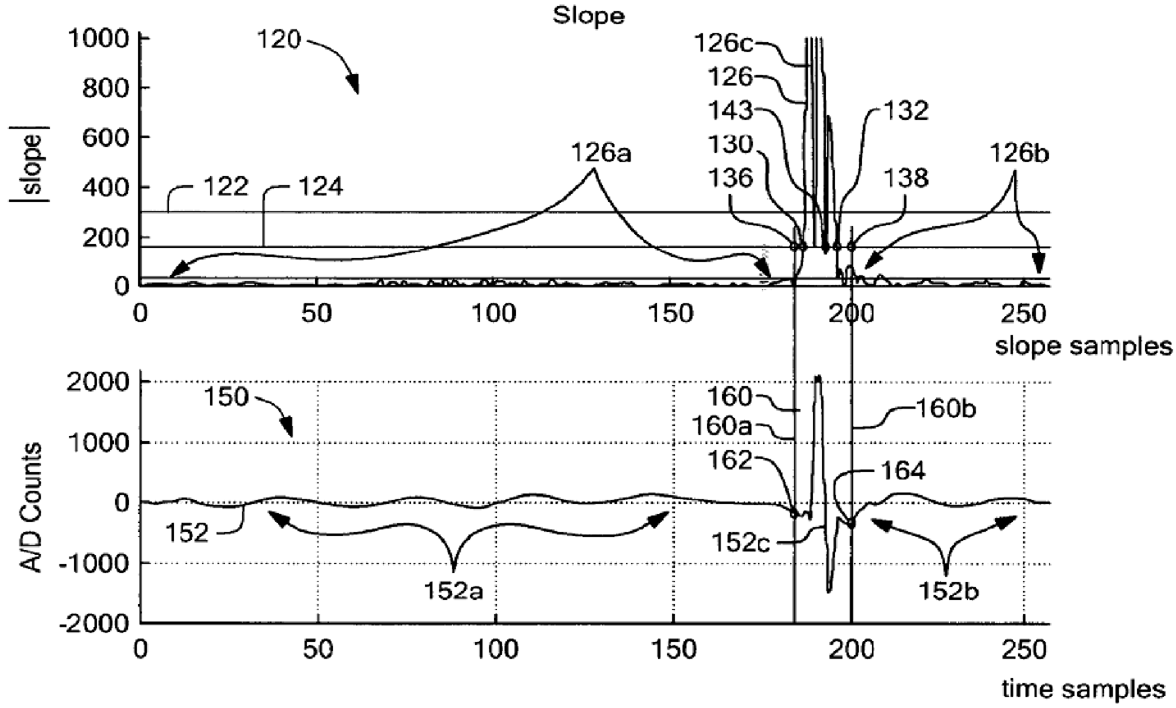


Figure 3.1.8.2: Interference detector zone

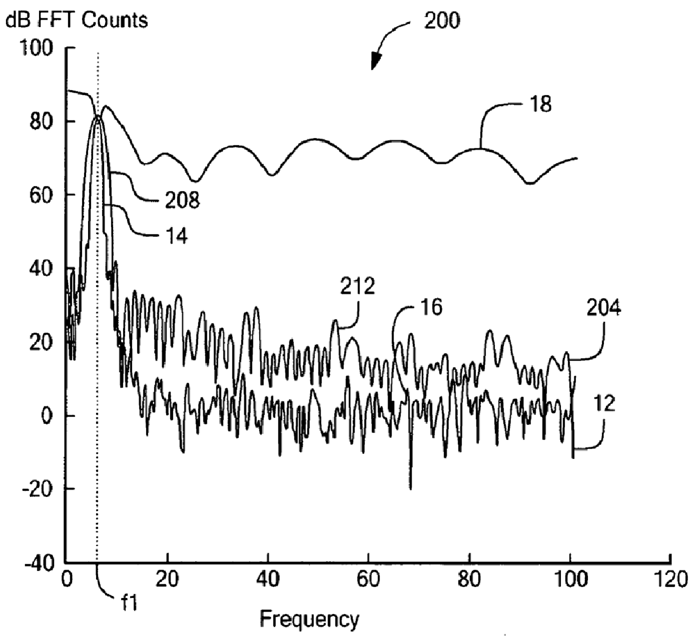


Figure 3.1.8.3: Not interfered receive signal

Signal (12) in Figure (3.1.8.3) is a not interfered receive-signal. The peak (14), caused by a target reflection, is clearly visible at frequency f1. Signal (18) shows the same signal with heavy interference, what avoids a high probability for indicating the target peak at f1. Signal (212) is the result of applying the above described interference mitigation method to the signal (18). The noise floor is indeed higher than the noise floor of signal (12) and the target peak is a little bit wider, but the target peak is still clearly visible.

Instead of zero padding, also a weighting function could be used to suppress the interference in the zone of interference. Also, the thresholds have not to be slope-values, they can be derivatives of every order as well as power levels.

General comments:
The idea to introduce thresholds dependent on derivatives is common praxis in the industry. This method is interesting, because it is easy to apply, but still effective. The observation of more derivatives can further increase the interference detection accuracy.

Patent reference in Bibliography	PREF08
Restriction to a specific radar type	FMCW, but could be adapted to others
Implementation effort	Medium, because the tuning of this method will need some time.
Side-effect with other methods	Nothing expected
Mitigation effect on TX path	no
Mitigation effect on RX path	Yes, zero padding or replacement by other values
Computational effort	medium
Interference mitigation category	Detect and repair (time domain)
Harmonization needed	No
MOSARIM relevant	yes
Range of mitigation effect	~40dB (Figure 3.1.8.3), depends on kind of interference

3.1.9 PREF09 – Pulse Doppler radar interference reduction method for vehicle anti-collision or building security system

Abstract:
In this patent the inventor proposes to code the phase of the transmitted pulse at a Pulse-Doppler-radar. At the receiving unit the received pulse will be decoded correspondingly. With this method disturbances will be decreased significantly. This method also increases the range for non-ambiguous determination of targets. According to the author the third advantage is that a lot of radar sensors based on the same technology can run close by each other without disturbing the others.
The author proposes to set the zero phases at transmitter to φ or to φ +180°. This results in a complex pointer for phi to $S_i = A \cdot e^{j(\varphi)}$ and for φ + 180° to $S_i = A \cdot e^{j(\varphi+180°)} = -A \cdot e^{j(\varphi)}$.
According to the inventor this results in a general formula for the complex pointer to $S_i = p_i \cdot A \cdot e^{j(\varphi)}$, whereby p_i is either +1 or -1. At the receiving stage the echo the transmitted pulse S_i has to be multiplied with $-p_i$.
The inventor also proposes to realize this phase coding by a pseudo noise sequence to suppress Multiple – Around – Echoes and to use different codes for several radars for additional reduction of disturbance.

Patent reference in Bibliography	PREF09
Restriction to a specific radar type	Described for pulse Doppler radar
Implementation effort	Small, because only the software has to be changed
Side-effect with other methods	Nothing expected
Mitigation effect on TX path	no
Mitigation effect on RX path	yes
Computational effort	Slight higher
Interference mitigation category	Coding domain
Harmonization needed	No, different coding even improves the mitigation of interference
MOSARIM relevant	yes, idea is upgradable
Range of mitigation effect	~15dB (prevent occurrence of ghost targets, but results in increase of noise floor)

3.1.10 PREF10 – Interference determination method and FMCW Radar using the same

This patent is very similar to patent US20060125682A1 that is also discussed in this deliverable. Instead of talking about slopes for comparisions with thresholds, this patent talks about variations and comparision with thresolds. The variation is the difference in voltage between two samples in a row.
However, this interference mitigation method is also applied for an FMCW radar. The main idea of this method is to sample the IF-signal with two times the maximum appearent beat-frequency and compare the variation of the sampled signals with a threshold. The maximum appearent beat-frequency is determined by the maximum range and maximum relative velocity to be measured by the radar system. The reason why the sampling rate has to be at least (or maybe even better equal) two times the maximum beat frequency is, that a non interfered sinusodial IF waveform at the mixer output will always have a variation of about the normal amplitude. If there is interference, what results in increased IF frequency components, this variation is exceeded. Figure (3.1.10.1) shows the non interfered signal section on the left and the interfered signal section on the right.

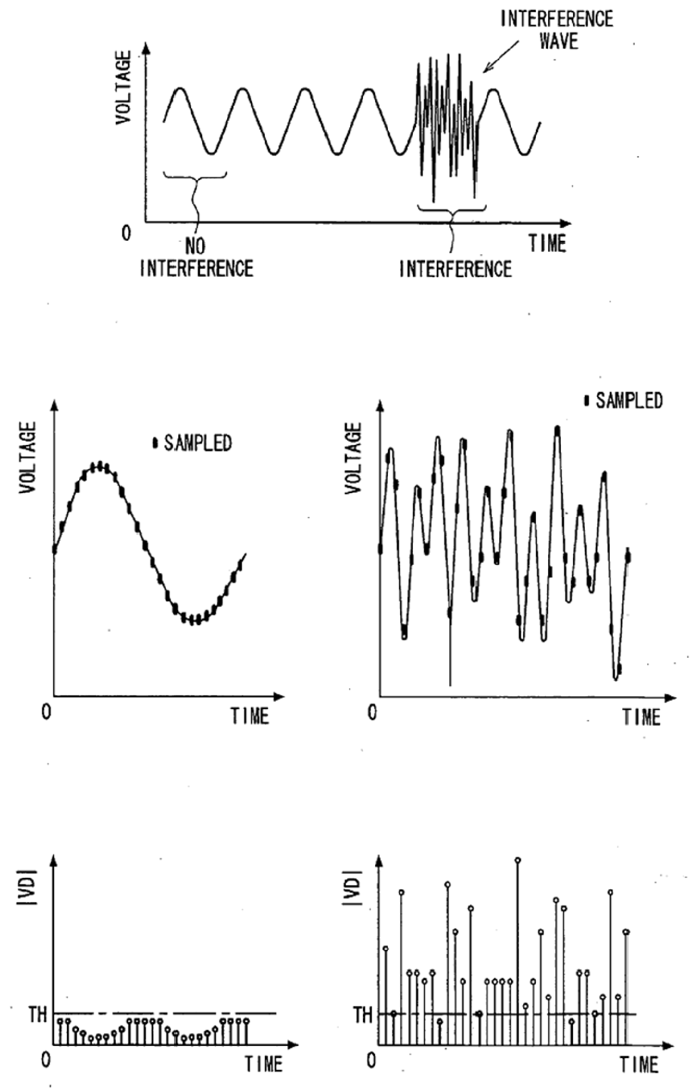


Figure 3.1.10.1: Non-interfered and interfered signal section

The flow chart of this interference mitigation concept is shown in Figure (3.1.10.2). The handling is quiet similar to the other Denso patent US20060125682A1. Both use zero padding for eliminating the interference in radar signals. Here, this happens in (S140) of Figure (3.1.10.2).

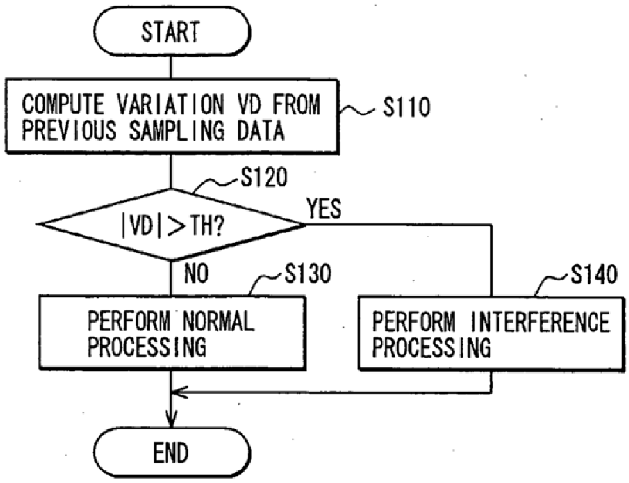


Figure 3.1.10.2: Flow chart of interference mitigation concept

General comment:
This patent is more an extension of Denso's first patent. Here, the slope is abstracted to a variation and the interference elimination itself is better described in Denso's first patent. But both patents US20060125682 A1 and US20070018886 A1 are interessting and can be combined.

Patent reference in Bibliography	PREF10
Restriction to a specific radar type	Signal sampling radar systems
Implementation effort	small
Side-effect with other methods	Nothing expected
Mitigation effect on TX path	Yes, carrier frequency change
Mitigation effect on RX path	Yes, zero padding
Computational effort	small
Interference mitigation category	Detect and repair (time domain)
Harmonization needed	no
MOSARIM relevant	yes, can maybe used in combination
Range of mitigation effect	t.b.d.

3.1.11 PREF11 – Interference Avoidance System for Vehicular Radar System

A short overview of the radar system, to what the mitigation method was applied:
The reviewed patent US005280288A introduces a software-algorithm mitigation method that can possibly by useful for different kinds of radar systems if it is adapted. In this patent, the mitigation method is applied for a time division multiplexed radar system that successively transmits a signal consisting of two (or more) sections with constant frequencies.
At the receiver, the difference in frequency of transmitted and received signal is created with a mixer-device. This difference-frequency is exactly zero for a relative velocity of zero (=not moving target). If there is a relative moving between victim and target, then the difference-frequency is the Doppler-frequency-shift caused by the observed target. Next, the mixer-output signal is sampled and transformed into frequency domain with an FFT. Here, the

relative velocity and range are calculated by the equations listed in column 13 in patent US005302956A, what is closely related to the patent US005280288A.

The interference mitigation method of patent US005280288A:

The basic principle of this interference mitigation method is to change the carrier frequency in the case of interference. The decision, if there is interference or not, is made by the comparison of a predetermined threshold with the receive signal's noise level power, which is calculated out of the receive signal's FFT. If it is decided that interference is present (noise level in receiver bandwidth exceeds threshold), the carrier frequency is changed. Then, again the receive signal is checked for interference and the carrier frequency is changed again, until there is no more interference in the receiver bandwidth, or the carrier frequency was changed to often. In this patent, up to 4 carrier changes are allowed. The threshold itself is determined by the averaging of calculated noise-level powers at different, random carrier frequencies, or is simply set to values out of look up tables.

To apply the mitigation method fast and not to waste much time, there are done checks for interference with as few samples as possible. So the system does not have to process all the data first, only for coming to the conclusion, that there is too much interference and the results cannot be further used. In this patent, the check for interference is done after 1024, 2048 and 4096 samples, and the calculation of the relative velocity and range are done in parallel after 1024, 2048 and 4096 samples.

Figure (3.1.11.1) shows the block diagram for the applied mitigation method. The processing of 2048 and 4096 samples is only done, if there is no interference over a certain time.

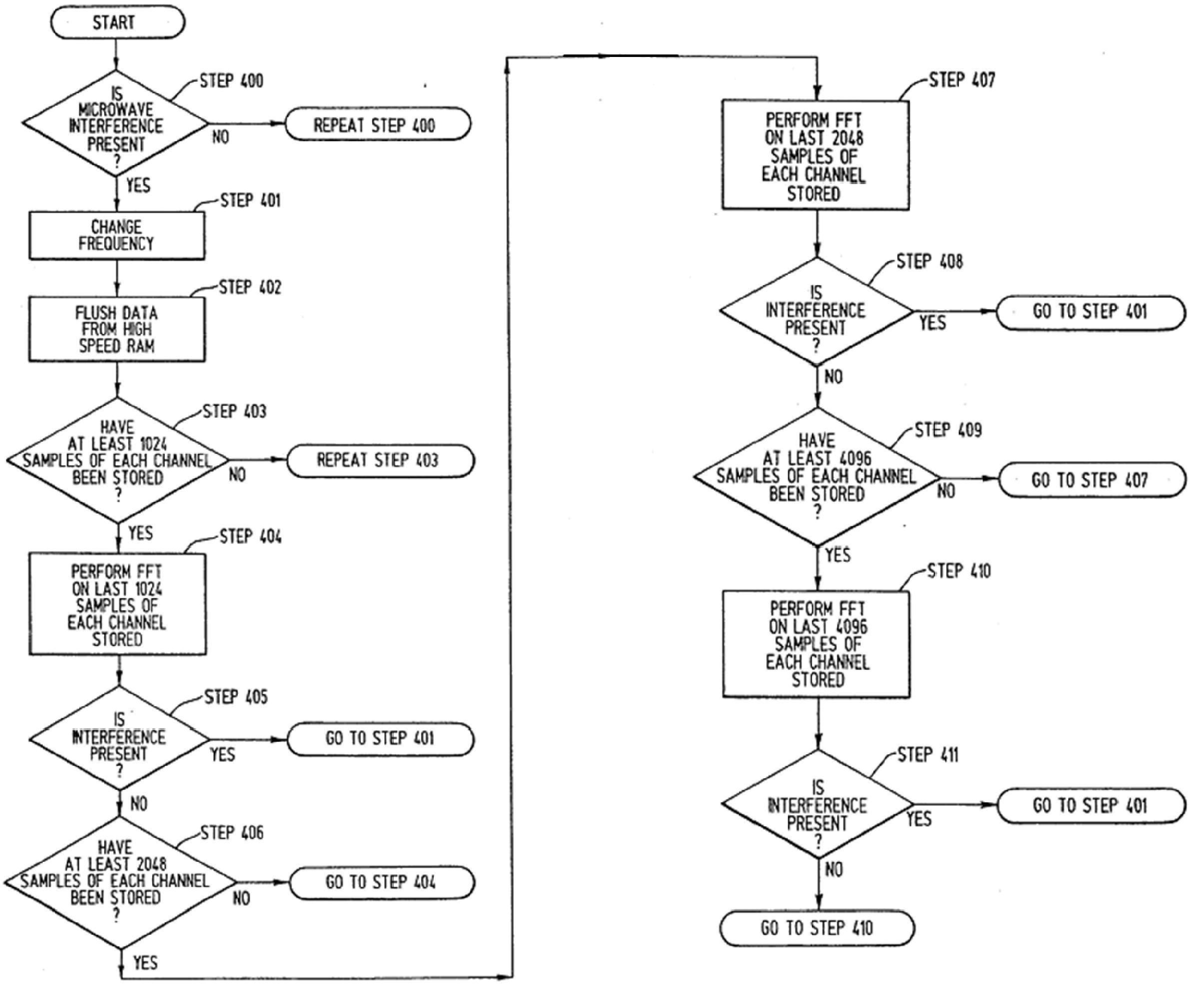


Figure 3.1.11.1: Block diagram of the applied mitigation method

General comment:
This method is useful for the Radar presented in the patent US005302956A, because the Doppler resolution increases with observing-time, but the calculations can also be done with less samples and lower Doppler resolution. This could be useful to maintain tracking, maybe. For other kind of radars this "stepped" mitigation method could maybe adapted for a tradeoff between interference probability and Doppler-resolution.

Patent reference in Bibliography	PREF11
Restriction to a specific radar type	Stepped frequency with longer constant frequencies
Implementation effort	small
Side-effect with other methods	Nothing expected, may be combined with others
Mitigation effect on TX path	Yes, carrier change
Mitigation effect on RX path	Yes, minimizing time for interference detection
Computational effort	small
Interference mitigation category	Detect and avoid (frequency domain)
Harmonization needed	no
MOSARIM relevant	yes, can maybe used in combination
Range of mitigation effect	t.b.d.

3.1.12 PREF12 – Vehicular distance-warning radar

Abstract:
In this patent the inventor proposes to use a specific 45 degree linear polarization for both the transmit and receive antenna of a vehicular distance warning radar. While the power reflected from obstacles in front of the radar device is not affected by the 45 degree slant polarization as both the transmit and receive antenna operate in the same electric field-vector plane the interference effect from oncoming vehicles equipped with the same radar device is drastically reduced due to the cross-polarization effect (see 2.1). The victim radar receive antenna (with 45 degree polarization) sees the polarization of the oncoming interference radar at 135 degree that is 90 degree shifted in phase and thus results in the minimum susceptibility for interference. The invention can be likewise used for rearward-looking radars of vehicles driving in the same direction. For this case the rearward-looking radars shall have a 135 degree slant polarization to minimize the interference effect.

Patent reference in Bibliography	PREF12
Restriction to a specific radar type	No, can be used for any kind of vehicular radar
Implementation effort	small, because realized in hardware by specific antenna design
Side-effect with other methods	Nothing expected, may be combined with others
Mitigation effect on TX path	yes
Mitigation effect on RX path	yes
Computational effort	negligible
Interference mitigation category	Polarization domain
Harmonization needed	Yes, because polarization must be identical for all devices
MOSARIM relevant	yes, idea is upgradable
Range of mitigation effect	10 dB to 30 dB

3.1.13 PREF13 – Radar system for detecting surroundings with compensation of interfering signals

Abstract:
The scope of this patent is limited to the FMCW radar principle. The basic idea is to eliminate or reduce the effect of an interfering radar signal by applying a dithering effect to the FMCW radar operational parameters. At least one of the following parameters is therefore changed over time:

- The start time of the frequency slope
- The delay time until the IF-signal is first sampled with the analog-to-digital converter
- Time variation of the transmit and receive interval
- The idle time between the up- and down- frequency slopes
- The steepness of the slope and whether the up or down slope starts first
- The absolute start frequency of the up- and down-slope

By applying at least one of the above mentioned means the effect of an interfering signal will be reduced in the frequency domain (after the FFT processing) by smearing its interference power in a larger bandwidth. A significant reduction may only occur if the interference signal is uncorrelated to the changing process of the parameters. With FM slope start time variation By another claim of this patent interference effects are further reduced by applying non-linear filtering and averaging over several FFT spectra.

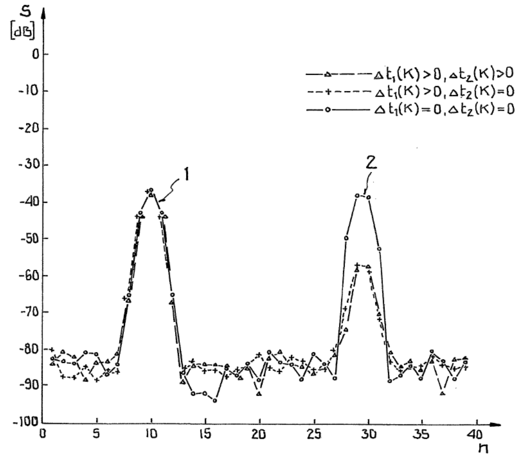


Fig. 3.1.13.1: Simulation of the reduction of the interference signal (2) by 18 dB with time variation of the transmit and receive interval

Patent reference in Bibliography	PREF13
Restriction to a specific radar type	Only possible for FMCW radar type
Implementation effort	Medium hardware effort and large processing effort for averaging over multiple FFT spectra
Side-effect with other methods	Nothing expected, may be combined with others
Mitigation effect on TX path	no
Mitigation effect on RX path	yes
Computational effort	Medium to large
Interference mitigation category	Time and frequency domain
Harmonization needed	No, parameter variation should be uncorrelated
MOSARIM relevant	yes
Range of mitigation effect	20 dB

3.1.14 PREF14 – Method for the suppression of disturbances in systems for detecting objects

The scope of this patent is limited to pulse-Doppler radar principle. The pulse repetition frequency of the Doppler radar is pseudo-noise coded to reduce interference with other radar systems. Nevertheless interference is still possible and the interference effects manifest by sharp peaks in the time signal. With the use of non-linear filtering (e.g. multi-stage median filters) interference peaks can be reduced, as shown in Fig. 3.1.14.1.

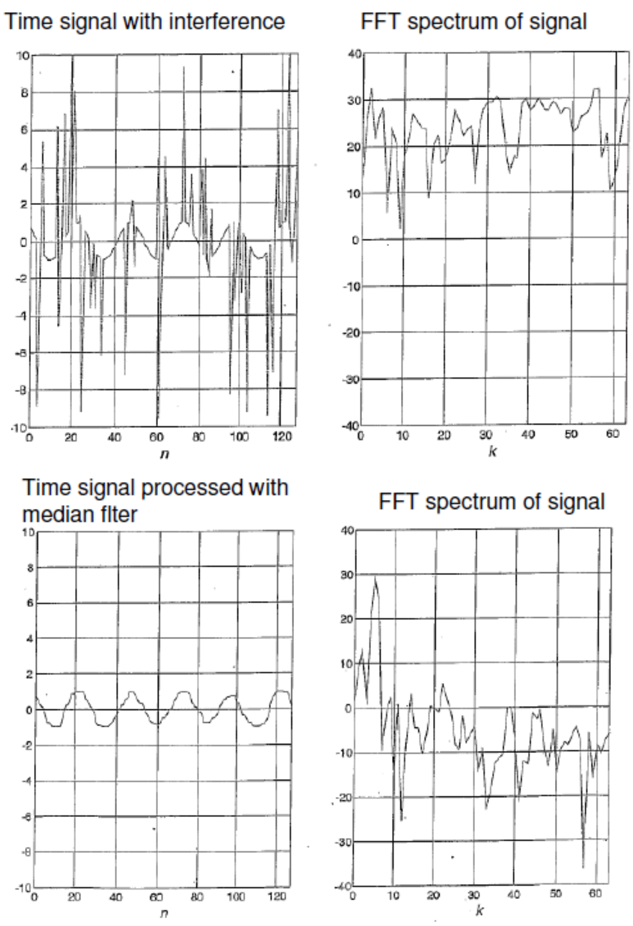


Fig. 3.1.14.1: Reduction of interference peaks in a pseudo-noise pulse-Doppler radar signal by median filtering of the time signal

Patent reference in Bibliography	PREF14
Restriction to a specific radar type	Only possible for pulse-Doppler radar type
Implementation effort	Medium hardware and processing effort
Side-effect with other methods	Nothing expected, may be combined with others
Mitigation effect on TX path	yes, PN coding
Mitigation effect on RX path	no
Computational effort	Medium
Interference mitigation category	Time domain
Harmonization needed	no
MOSARIM relevant	yes
Range of mitigation effect	20 dB

3.1.15 PREF15 – Automotive radar system with anti-interference means

Described in this patent is a method to detect interference from other radars and a method for finding unused frequency slots. Fig. 3.1.15.1 shows the method for detecting interference from other radars based on the radar's FFT spectrum (FMCW radar). Upon the detection of interference other vehicles are queried either directly or indirectly via a base station to find an unused frequency slot for the disturbed radar (see Fig. 3.1.15.2).

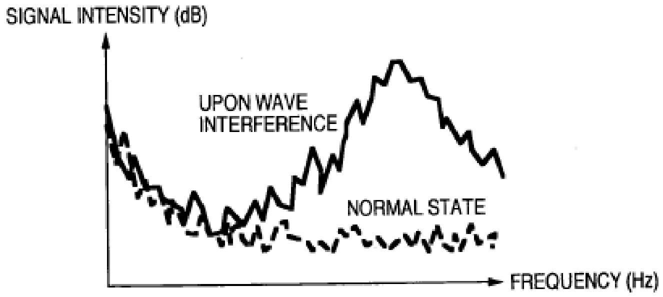


Fig. 3.1.15.1: Detection of interference from other radars based on the radar's FFT spectrum (FMCW radar).

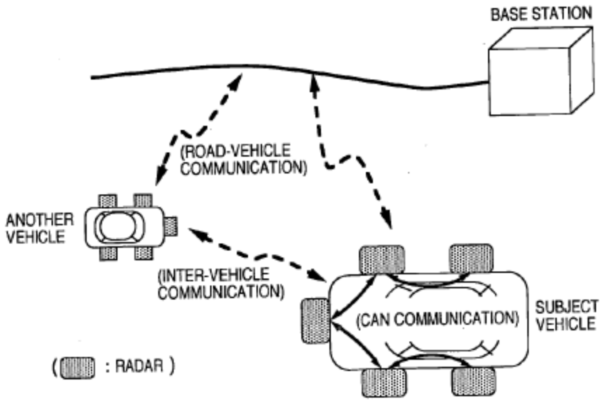


Fig. 3.1.15.2: Communication scheme: Either direct communication between vehicles or indirect communication between vehicles via a base station

Patent reference in Bibliography	PREF15
Restriction to a specific radar type	FMCW radars
Implementation effort	large, since communication between vehicles is required
Side-effect with other methods	Nothing expected, may be combined with others
Mitigation effect on TX path	yes
Mitigation effect on RX path	yes
Computational effort	In the radar sensors: Limited
Interference mitigation category	Detect and avoid, communicate and avoid (frequency domain)
Harmonization needed	Yes, all vehicles need to be able to communicate
MOSARIM relevant	Depends on whether communication between vehicles will be considered as an option
Range of mitigation effect	Method to avoid interference by the use of separate frequency bands; high mitigation expected

3.1.16 PREF16 – Interference rejection method for an automotive radar CW/ICC system

The patent describes a method for FMCW radars to detect and eliminate so-called transient pulses which can e.g. be generated by interference from other FMCW radars. Fig. 3.1.16.1 shows such a transient pulse in the samples of the intermediate frequency signal of a FMCW radar. The method locates the transient pulse and sets the affected samples to zero. The signal is then interpolated to fill the gap. The reduction of the noise floor in the FFT spectrum of the intermediate frequency signal which is achieved by the method can be seen in Fig. 3.1.16.2.

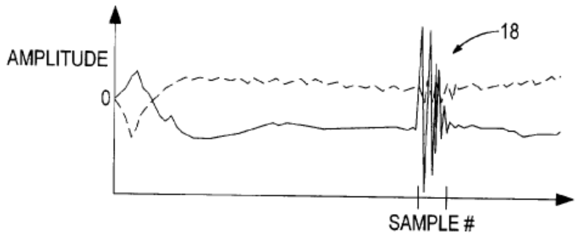


Fig. 3.1.16.1: Transient pulse in the samples of the intermediate frequency signal of a FMCW radar

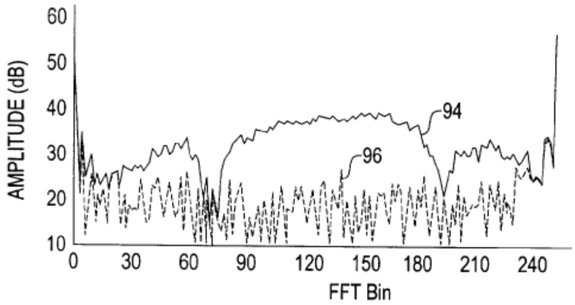


Fig. 3.1.16.2: Comparison between the disturbed FFT spectrum of the intermediate frequency signal and the FFT spectrum obtained after applying the method.

Patent reference in Bibliography	PREF16
Restriction to a specific radar type	FMCW radars
Implementation effort	low (digital signal processing of the samples before the FFT)
Side-effect with other methods	Nothing expected, may be combined with others
Mitigation effect on TX path	no
Mitigation effect on RX path	yes
Computational effort	Should not be too large
Interference mitigation category	Detect and repair (time domain)
Harmonization needed	no
MOSARIM relevant	Yes, since it should be relatively easy to implement this measure in existing FMCW radars
Range of mitigation effect	Theoretically the interference can be completely eliminated

3.1.17 PREF17 – Procedure for the elimination of interference in a radar unit of the FMCW type

The patent describes a method to detect and eliminate so-called transient pulses which can e.g. be generated by interference from other FMCW radars. Fig. 3.1.17.1 shows such a transient pulse in the samples of the intermediate frequency signal of a FMCW radar. The method locates the transient pulse and sets the affected samples to zero. The signal is then extrapolated from the previous samples to fill the gap. The undisturbed signal and the extrapolated signal are compared in Fig. 3.1.17.2. It can be seen that the extrapolated signal matches the undisturbed signal well.

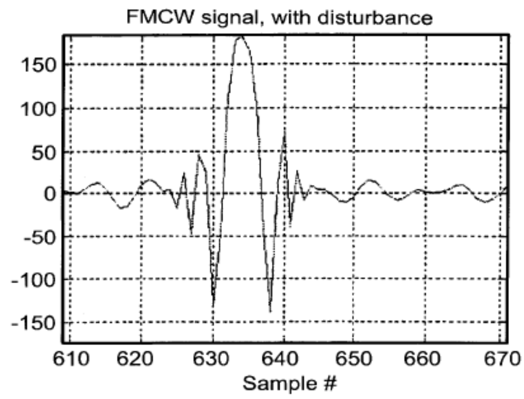


Fig. 3.1.17.1: Transient pulse in the samples of the intermediate frequency signal of an FMCW radar.

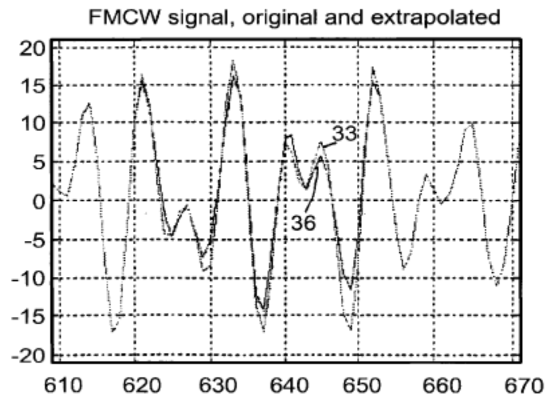


Fig.3.1.17. 2: Comparison between the extrapolated signal and the original (undisturbed) signal.

Patent reference in Bibliography	PREF17
Restriction to a specific radar type	FMCW radars
Implementation effort	low (digital signal processing of the samples before the FFT)
Side-effect with other methods	Nothing expected, may be combined with others
Mitigation effect on TX path	no
Mitigation effect on RX path	yes
Computational effort	Should not be too large
Interference mitigation category	Detect and repair (time domain)
Harmonization needed	no
MOSARIM relevant	Yes, since it should be relatively easy to implement this measure in existing FMCW radars
Range of mitigation effect	Theoretically the interference can be completely eliminated

3.1.18 PREF18 – FMCW Radar Device and Method for Detecting Interference

This interference mitigation method makes use of the increasing high-frequency noise floor at the output of the receiver-mixer in the case of present interference. The interference mitigation method is said to be effective against interference from FMCW, multiple frequency CW, pulse and spread spectrum Radars.

A short overview of the radar system, to what the mitigation method was applied:
This patent introduces an interference mitigation method, applied for a standard FMCW Radar device. The victim radar transmits a sinusoidal signal, swept linearly in time. This signal is reflected by an observed target and is received by the antenna of the victim receiver-stage. Additional, the victim receiver antenna receives some interfering signals, which are superimposed with the use-signal. The newly formed signal is now mixed with the original transmitted signal and the result is the IF-frequency. The IF-Frequency is now transformed into frequency domain by an FFT.

The interference mitigation method of patent US20060181448A1:
The starting point of this mitigation method is the FFT. The FFT is divided into two sections, a "target detection frequency range" and a "high frequency range", see Figure (3.1.18.1).

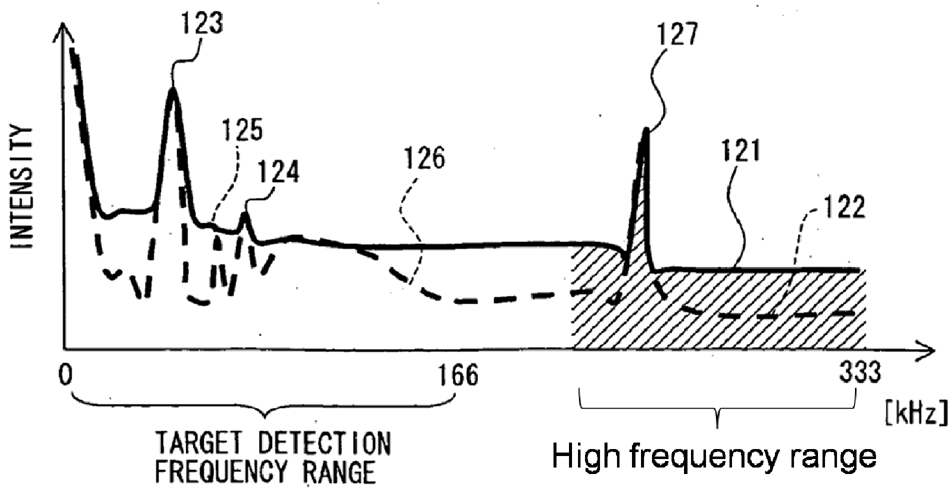


Figure 3.1.18.1: Two FFT sections

There are several points in Figure (3.1.18.1) that have to be remarked. The solid line represents the FFT of the interfered IF signal, the dashed line represents the FFT of the IF signal without interference. 123 and 124 show found targets within the detection range. Also 125 is a target, but not visible if interference is present. The zone around 126 is slightly wider than other targets, what is caused by multipath phenomena like reflections from the side of the road. 127 is a target outside the detection range, what is still present in this FFT. This can only happen, if there is a very large object with a surface that stands perpendicular to the incident radar wave.
The authors of this patent pretend that there is no synchronization between any radar system, and the probability for an occurrence of ghosts extremely low due to non-idealities, so the interference will only result in an increased noise floor over both frequency bands in Figure (3.1.18.1).
Now the interference detection and mitigation works the following way:
The noise floor in the high frequency range is observed and the magnitude per frequency is added up. The high frequency range is observed because here it is possible to sum the magnitudes per frequency over a wider frequency span, without having very much peaks from

targets in it. If the sum of the magnitudes exceeds a predetermined threshold, interference is indicated. To avoid the interference (here it is called "measurement against interference"), the carrier frequency of the radar is changed (frequency hopping), or the polarization of the antenna is changed. Figure (3.1.18.2) shows the algorithm in a flow chart.

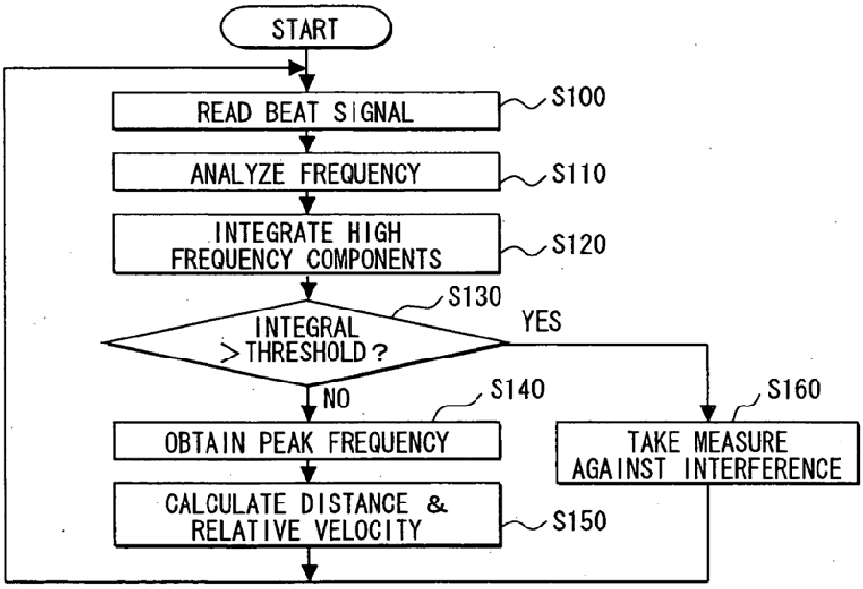


Figure 3.1.18.2: Flow chart of algorithm

The threshold can be determined in different ways. One possibility is to gain information about the noise floor from other FMCW receivers at the vehicle, so there can be calculated an interference/noise mean for the use as a threshold. Figure (3.1.18.3) shows the applied threshold to a FFT.

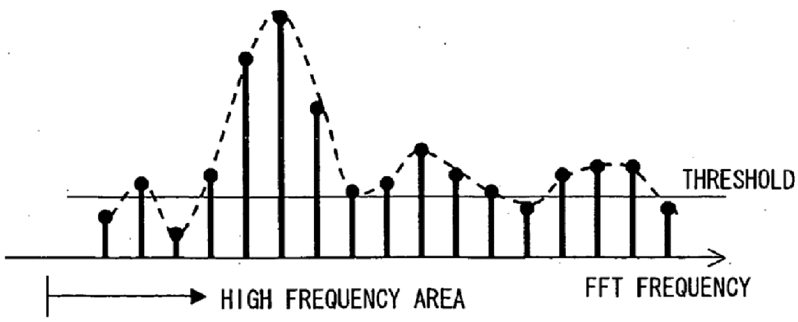


Figure 3.1.18.3: Applied threshold to a FFT

General comments:

In typical FMCW radar system there is a filter after the maximum detection range that cuts off all frequencies above Nyquist criterion. Because of that, the here introduced method will likely be used separately on an own path after the mixer before the anti aliasing low pass (this is mentioned in a short sentence in the patent). Then it is possible to apply a band-pass filter to focus on the relevant frequencies for further interference detection by the microcontroller.
The important point of this detection/mitigation method is that it is applied in a higher bandwidth region, which is less "infested" with targets and will lead to a more reliable threshold determination.

Patent reference in Bibliography	PREF18
Restriction to a specific radar type	FMCW, but could be adapted to other Radars
Implementation effort	low
Side-effect with other methods	Nothing expected, may be combined with others

Mitigation effect on TX path	yes, frequency change, polarization change
Mitigation effect on RX path	no
Computational effort	small
Interference mitigation category	Detect and avoid (polarization domain, frequency domain)
Harmonization needed	Yes, if polarization is switched for interference mitigation
MOSARIM relevant	yes
Range of mitigation effect	t.b.d.

3.1.19 PREF19 – Adding error correction and coding to a radar system

Described in this patent are the use of intra-pulse modulation to achieve a finer range resolution and the use of inter-pulse modulation for the decoupling of different (pulsed) radars. A pulse sequence with only intra-pulse modulation is shown in Fig. 3.1.19.1, the pulse sequence in Fig.3.1.19.2 has both intra-pulse and inter-pulse modulation. Different radars cannot be completely decoupled by this measure, but interference from other radars is reduced significantly since the pseudo-noise codes used for the inter-pulse modulation have a low cross correlation. The principle requires integration over one period of the code. Longer codes achieve a greater mitigation factor, the trade-off is therefore between mitigation factor and measurement duration.

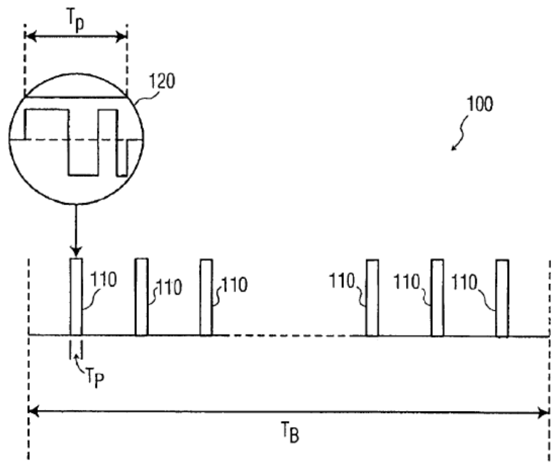


Fig. 3.1.19.1: Pulse sequence with only intra-pulse modulation.

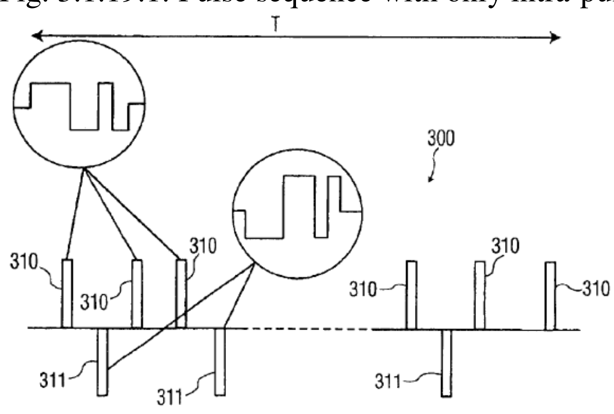


Fig. 3.1.19.2: Pulse sequence with both intra-pulse and inter-pulse modulation.

Patent reference in Bibliography	PREF19
Restriction to a specific radar type	Pulsed radars
Implementation effort	Requires a binary phase shift keying (BPSK) modulator
Side-effect with other methods	Nothing expected, may be combined with others
Mitigation effect on TX path	yes
Mitigation effect on RX path	yes
Computational effort	Requires the generation of a pseudo-noise sequence (one period of a pseudo-noise code)
Interference mitigation category	Coding domain
Harmonization needed	Yes, radars need to use codes from the same set of codes
MOSARIM relevant	Yes
Range of mitigation effect	Depends on the code length (longer codes achieve a greater mitigation factor)

3.1.20 PREF20 – Method for operation of a radar device

The scope of this patent is limited to pulse-Doppler and FSK radar principle. A special evaluation unit analyzes the received radar signal and determines whether an interference signal is present or not by plausibility checks. In case the evaluation unit detects the presence of an interferer the radar operation frequency is changed to another value that is within the maximum allowed operational bandwidth of the radar. With this counter-measure applied a maximum of one processing cycle can be corrupted. The radar operation frequency remains at its new value until further interference is detected. Then either a higher or lower next operation frequency is chosen.
The principle of operational frequency change is shown in Fig. 3.1.20.1.

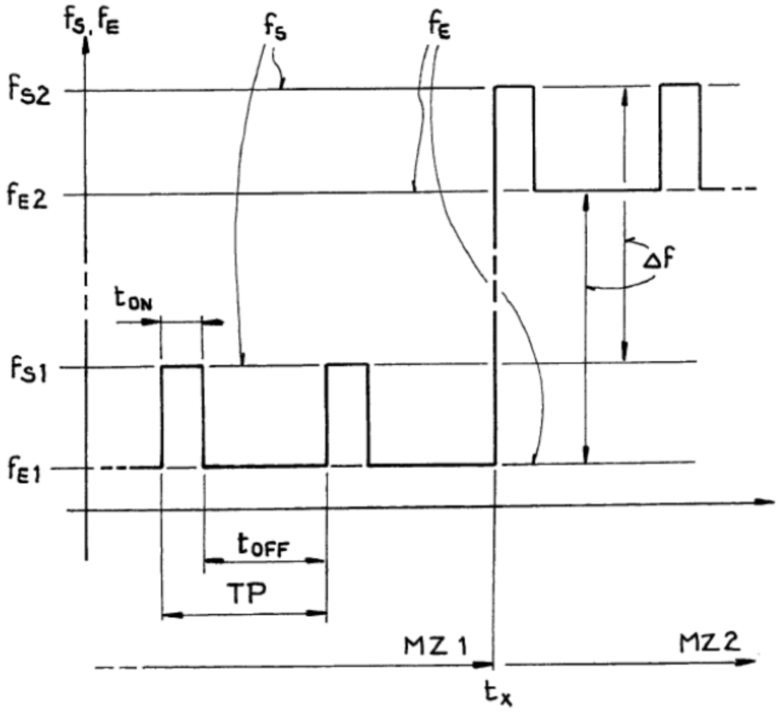


Fig. 3.1.20.1: Operational frequency change of a pulse-Doppler radar that has detected the presence of an interferer (f_S = transmit frequency, f_E = receive frequency, TP = pulse repetition frequency, MZ = processing cycle, t_x = interference detected)

Patent reference in Bibliography	PREF20
Restriction to a specific radar type	Only possible for pulse-Doppler and FSK radar type
Implementation effort	Medium hardware only
Side-effect with other methods	Nothing expected, may be combined with others
Mitigation effect on TX path	yes
Mitigation effect on RX path	no
Computational effort	negligible
Interference mitigation category	Detect and avoid (frequency domain)
Harmonization needed	No
MOSARIM relevant	yes
Range of mitigation effect	very high as long as free frequencies are available

3.1.21 PREF21 – Bridge detecting and false warning suppressing method for motor vehicle, involves suppressing controller of speed controlling system changing driving conditions of vehicle, when identified objects are classified to pre-set object class

Abstract:
In this patent the inventor proposes a method to detect bridges and to suppress fail warnings of a speed controlling system due to bridge targets.
The method involves detecting measured values concerning to a driving condition of a moving vehicle and representing the measured values in an evaluable measured value table. An analysis of the driving condition represented in the table is implemented, and objects are identified using a number of criteria characterizing the objects (distance, speed, acceleration, place of origin, life cycle of object, radar cross section). The identified objects are classified into a set of object classes. A false warning of the speed controlling system changing the driving conditions of the vehicle is suppressed, when the identified objects are classified to a pre-set object class.

Patent reference in Bibliography	PREF21
Restriction to a specific radar type	No, can be used for any kind of vehicular radar
Implementation effort	Small, just additional software algorithm
Side-effect with other methods	Possible, only uninteresting static targets will be removed
Mitigation effect on TX path	-
Mitigation effect on RX path	yes
Computational effort	Additional analysis algorithm necessary
Interference mitigation category	Coding domain
Harmonization needed	No, because algorithm does not influence other sensors
MOSARIM relevant	yes, idea is upgradable
Range of mitigation effect	Removing of uninteresting static targets

3.1.22 PREF22 – Radar device and methods for suppression of disturbance of a radar device

Abstract:
In this patent the inventor proposes a setup for a radar sensor including transmitting and receiving path. The inventor proposes to decrease disturbance by using a code to delay the transmitted pulse (23) and to delay reference signal (carrier) which will be mixed with the received pulse (25). This delay should be generated by a pseudo noise code generator (13).

According to the inventor this results in an improvement of S/N ratio. The detection of false targets will also be decreased.

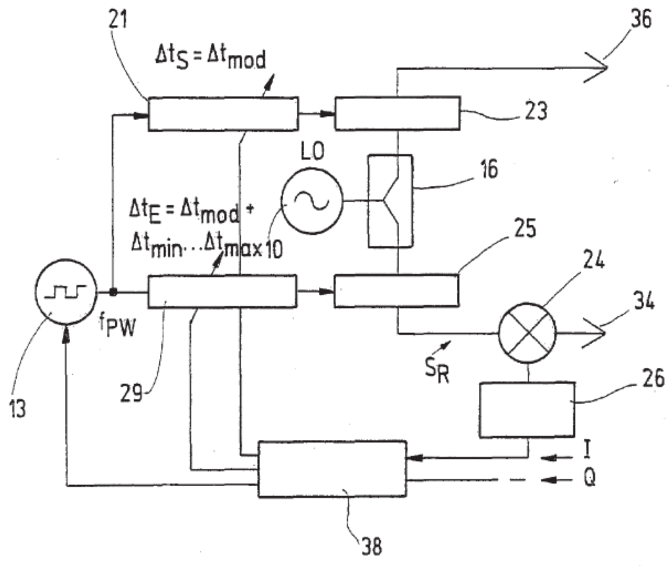


Fig. 3.1.22.1: Example architecture

The inventor also proposes to change the code cyclically to increase suppression of disturbance.
The inventor also suggests an additional method for suppressing disturbance by the usage of amplitude shift keying, phase shift keying and polarization of the signal.

Patent reference in Bibliography	PREF22
Restriction to a specific radar type	Pulse radar or radar with chirp sequences
Implementation effort	Additional Software code has to be implemented
Side-effect with other methods	not known
Mitigation effect on TX path	no
Mitigation effect on RX path	yes
Computational effort	Not negligible, additional software for coding has to be implemented
Interference mitigation category	Time domain
Harmonization needed	no, different code for each radar sensor leads to better results between several sensors
MOSARIM relevant	yes
Range of mitigation effect	~ 10dB

3.2 Conference paper database

3.2.1 CREF01 – Reduction of Interference in Automotive Radars using Multiscale Wavelet Transform

Abstract:

A technique is presented to minimise false decisions in automotive radars operating in close proximity. The technique also reduces the requirement on the power of the radar as signals can be detected with very low signal to noise ratios. The signal processing is achieved in real time using a field programmable array.

Short Explanation:

The presented Algorithm uses the Wavelet Transform to determine the position of pulse edges (rising and falling). Only if the distance between the rising and the falling edge matches the expected value (i.e. the width of the transmitted pulse) the received signal is accepted as a valid reflection. In some sense the proposed technique can therefore be regarded as a form of matched filtering.

Paper reference in Bibliography	CREF01
Restriction to a specific radar type	Pulsed Radars
Implementation effort	medium, only signal processing needs adaption
Side-effect with other methods	nothing expected, may be combined with others
Mitigation effect on TX path	no
Mitigation effect on RX path	yes
Computational effort	high
Interference mitigation category	Detect and omit (time domain)
Harmonization needed	no
MOSARIM relevant	yes
Range of mitigation effect	t.b.d.

3.2.2 CREF02 – Reduction of Interference in Microwave Automotive Radars

Abstract:

In this document the authors proposes to implement an algorithm which reduces the probability for false decisions and the requirement on the transmitted power. Thus, the possibility of interference is reduced. The presented techniques depend on transmitted radar signals with different pulse widths and different pulse repetition frequencies.

The algorithm is based on a wavelet analysis to detect the pulses which match the transmitter own pulse width at presence of noise and false jamming signals on the received target pulse. There are two stages for this algorithm. The Criterions for use of the first stage are a high SNR and a low density of false jamming signals. Stage 2 is used if stage 1 fails to detect target pulse edges. This can happen if there is a low SNR and a high density of false jamming signals.

The algorithm also reduces the required transmitted power, because a correct detection is possible at much lower S/N ratios. This results in a decrease of interference from neighbouring radars.

Patent reference in Bibliography	CREF02
Restriction to a specific radar type	No, can be used for any kind of vehicular radar
Implementation effort	Additional algorithm
Side-effect with other methods	possible
Mitigation effect on TX path	no
Mitigation effect on RX path	yes
Computational effort	Additional algorithm
Interference mitigation category	Coding domain
Harmonization needed	no, not needed for algorithm
MOSARIM relevant	yes
Range of mitigation effect	ca. 5dB

3.2.3 CREF03 – Research on Key Technologies for Collision Avoidance Automotive Radar

Abstract:

Anti-interference capability and low cost play decisive roles for the break-through on the market of collision avoidance automotive radar. With the increasing use of automotive radar, the mutual interference becomes an issue. This paper proposes a novel signal design and signal processing methods for automotive radar, which combine good anti-interference capacity and the low cost of conventional frequency modulated continuous wave (FMCW) radar. The radar signal is easy to be generated and its signal processing can be performed by Fast Fourier Transform (FFT) algorithm. So, the proposed new method is feasible and effective.

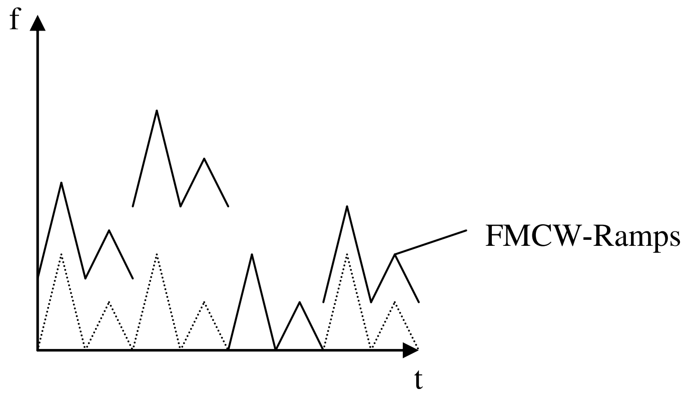


Figure 3.2.3.1: Illustration of the randomly shifted FMCW-ramps (solid) and standard ramps (dotted)

Short Explanation:

The authors describe a method to minimize interference by shifting the frequency of the transmitted signal pseudo randomly (Fig. 3.2.4). The actual frequency shift is computed via PN-sequences. Because of this random shift in frequency the probability of the interfering signal being mixed down into the IF- range of the victim receiver becomes much smaller. At the same time the interference signal becomes spread in frequency by averaging over several transmit sequences. This will increase the noise level of the victim receiver but prevents false alarms.

Paper reference in Bibliography	CREF03
Restriction to a specific radar type	FMCW radars
Implementation effort	low (frequency shift)
Side-effect with other methods	nothing expected, may be combined with others
Mitigation effect on TX path	yes
Mitigation effect on RX path	yes
Computational effort	low (generation of PN sequence)
Interference mitigation category	Frequency domain and time domain
Harmonization needed	yes, radars need to use codes from the same set of codes
MOSARIM relevant	Yes
Range of mitigation effect	t.b.d.

3.2.4 CREF04 – SS-FH signals used for very low interference in vehicular cruising control systems

The main idea of this paper from 1999 is a correlation based frequency-hopping radar with personalized frequency-hopping codes for each car to reduce the probability of relevant interference. The authors argue, that the number of different codes is so high, that it is nearly impossible to get relevant interfered from other radars (especially if they use the same radar architecture). This radar concept is realized in the following way:
There is a global clock for the radar.
For the transmit path, the global clock drives a code generator that directly modulates a VCO that is connected to the transmit-antenna. The code keeps unchanged for now.
For the receiver path, the global clock is delayed, and then guided to a code generator that generates the same code as in the transmit-path. This code generator directly drives the VCO in the receiver path.
By consequently increasing/decreasing the delay time in the receiver path, it is possible to scan the area observed by the radar.

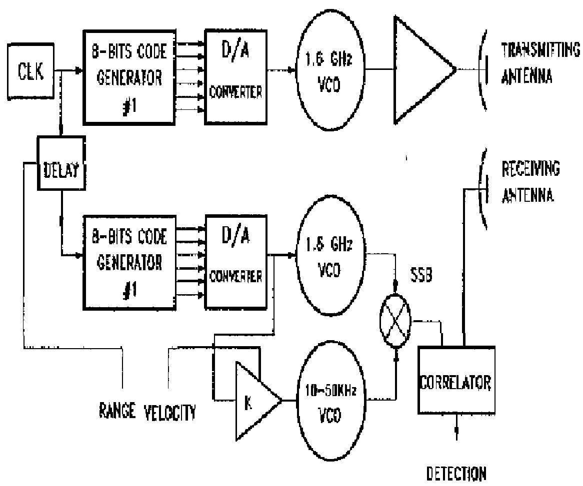


Figure 3.2.4.1: Basic system architecture of the correlation based frequency-hopping radar

General comments:

This architecture is interesting, if there is a plenty of time for detection of targets. But the antenna beam cannot be seen at once, so the area has to be scanned and the observing time on a target is strongly limited.

Patent reference in Bibliography	CREF04
Restriction to a specific radar type	no (can be adapted)
Implementation effort	high
Side-effect with other methods	Nothing expected
Mitigation effect on TX path	no
Mitigation effect on RX path	yes
Computational effort	medium
Interference mitigation category	Frequency domain and coding domain
Harmonization needed	no
MOSARIM relevant	Possibly
Range of mitigation effect	t.b.d.

3.2.5 CREF05 – Time-Varying Interference Suppression in Communication Systems Using Time-Frequency Signal Transforms

Abstract:
In this paper authors propose using Fourier transform generalization (GFT) to suppress linear or nonlinear interference in spread spectrum communication. The Fourier transformation (FT) is perfectly localized for complex sinusoid, signals with linear phase. However, the FT does not perform well for signals with nonlinear phase (time-varying signals with broadband nonlinear characteristic). Proposed is to use GFT which matches the interference in the time-frequency structure of the interference. The received data which is a superposition of the signal, noise and interference is transformed with GFT. The transformed data is threshold to suppress the peak that indicated the presence of interference. Remaining signal containing mostly transmitted signal and noise is transformed back with IGFT.

Patent reference in Bibliography	CREF05
Restriction to a specific radar type	(In paper) DSSS communication systems
Implementation effort	low
Side-effect with other methods	nothing expected
Mitigation effect on TX path	no
Mitigation effect on RX path	yes
Computational effort	moderate, calculation of GFT and IGFT
Interference mitigation category	Detect and repair (frequency domain)
Harmonization needed	no
MOSARIM relevant	yes, probably
Range of mitigation effect	t.b.d.

3.2.6 CREF06 – Wavelet domain communication system (WDCS) interference avoidance capability: analytic, modelling and simulation results

Abstract:
In this paper authors propose wavelet domain communication system (WDCS). Using Wavelet transformation the WDCS transmitter, see Fig. 3.2.6.1, estimates the electromagnetic spectrum and determines a spectral notching based on estimated characteristic. The power in each wavelet detail sub-band is compared to the noise power of environment. If it exceeds the noise by a defined factor the sub-band is nulled-out, otherwise the sub-band is retained. A pseudo-random phase weighing is applied to each coefficient creating a 'notched' vector of complex elements. The elements are scaled and inverse Wavelet transformed to create a time-domain waveform called basis function which is used for data modulation. The receiver generates remotely an identical basis function and uses it to estimate the communication symbols.

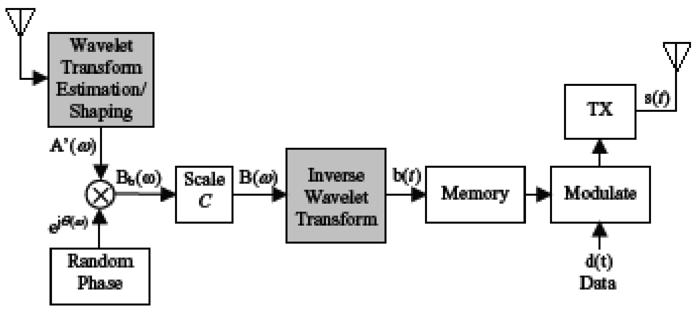


Fig.3.2.6.1: WDCS Transmitter Block Diagram

Patent reference in Bibliography	CREF06
Restriction to a specific radar type	The paper considers a communication system with antipodal and orthogonal modulation
Implementation effort	Low, signal processing
Side-effect with other methods	nothing expected
Mitigation effect on TX path	Yes
Mitigation effect on RX path	No
Computational effort	Moderate, wavelet transformation
Interference mitigation category	Time domain and frequency domain
Harmonization needed	no
MOSARIM relevant	Yes, depending on modulation
Range of mitigation effect	5.7-12.4dB depending on modulation

3.2.7 CREF07 – Novel pulse-sequences design enables multi-user collision-avoidance vehicular radar

Abstract:

A new, so-called Chaotic Pulse-Sequence Radar (CPSR) has been developed and implemented for short-range vehicular radar, designed to warn the driver of close-by overtaking vehicles (so-called 'blind-spot' warning). It employs a novel design of randomized signal generation and processing which overcomes problems of long-range returns from large reflecting structures and high-levels of interference from both similar and dissimilar radars in the same frequency channel/band. The new technique involves generation of long, non-deterministic pulse trains, composed of a large number of successive, relatively-short pulse-sequences having specially designed correlation properties, separated by random gaps. The statistically-defined unpredictability of such composite pulse trains required in a multi-user

scenario is derived from a very large number of pulse-sequences processed in the radar receiver to obtain near-vehicle range estimates. Field tests of a prototype radar confirm good and reliable performance of the technique, including its interference rejection capabilities.

Short Explanation:

The proposed long pulse sequences are built from short sequences of pseudo random behaviour. These short sequences must fulfil several criteria as a certain minimum distance or special cross correlation properties. Because of these restrictions there are relatively few good sequences and therefore the finally transmitted pulse train is concatenated from short sequences or their time inverted counterpart with a random delay.

Paper reference in Bibliography	CREF07
Restriction to a specific radar type	Pulsed radars
Implementation effort	Low
Side-effect with other methods	Nothing expected, may be combined with others
Mitigation effect on TX path	Yes
Mitigation effect on RX path	Yes
Computational effort	Moderate
Interference mitigation category	Time domain
Harmonization needed	Yes
MOSARIM relevant	Yes
Range of mitigation effect	Depends on the number of successive sequences, in the order of 10 dB

3.2.8 CREF08 – A Novel Transmit signal Based on High Range-Resolution Concept for FLAR or AICC System Applications

Abstract:

In this paper, a coded stepped-FMCW signal for mm-Wave Automotive Collision Warning radar (FLAR or AICC systems) applications is proposed, which offer high range resolution and multiple target detection probability, and good anti interference capability can be obtained as well. The waveform is easy to be generated digitally and its signal processing reduced the requirement of computational speed compared to conventional high resolution radars. We also suggested an error approach algorithm for multiple vehicle target detection and confirmed its usefulness in eliminating the false target by computer simulation.

Short Explanation:

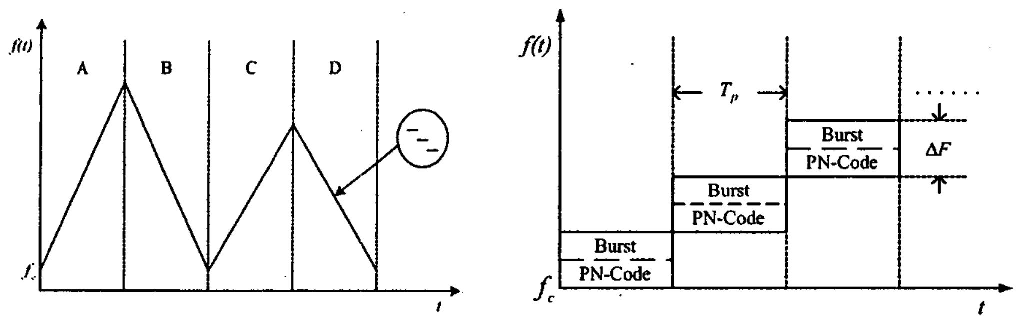


Figure 3.2.8.1: Illustration of the proposed FMCW sequences (left: overall, right: close up view of the up ramp)

As shown in Fig. 3.2.8.1 the authors propose to build the frequency ramps from short, PN-coded sequences. Therefore the proposed method can be regarded as a form of spread spectrum technique. This helps to reduce the impact of narrow band interferers depending on the length and bandwidth of the used sequence.

Paper reference in Bibliography	CREF08
Restriction to a specific radar type	FMCW radars
Implementation effort	Stepped FMCW with BPSK modulation
Side-effect with other methods	Nothing expected, may be combined with others
Mitigation effect on TX path	Yes
Mitigation effect on RX path	Yes
Computational effort	Special demodulation
Interference mitigation category	Coding domain
Harmonization needed	Yes, radars need to use codes from the same set of codes
MOSARIM relevant	Yes
Range of mitigation effect	Depends on the code length (longer codes achieve a greater mitigation factor)

3.2.9 CREF09 – Agile Digital Detector for RFI Mitigation

Abstract:

In this paper the authors propose a new type of detector capable of identifying low level radio frequency interference (RFI) and of reducing or eliminating its effect.
The agile digital detector (ADD) discriminates between RFI and natural thermal emission signals by directly measuring other moments of the signal than the variance that is traditionally measured. High order moments of the received signal are detected, from which characteristics of the probability distribution of its amplitude can be estimated. For a signal generated by thermal emission alone, the amplitude is Gaussian distributed. The presence of non-Gaussian distributed RFI can be detected by its influence on the high order moments.

Patent reference in Bibliography	CREF09
Restriction to a specific radar type	no
Implementation effort	medium to high (high order spectra)
Side-effect with other methods	no
Mitigation effect on TX path	no
Mitigation effect on RX path	yes
Computational effort	medium to high
Interference mitigation category	Only detection (frequency domain)
Harmonization needed	no
MOSARIM relevant	yes, probably
Range of mitigation effect	t.b.d.

3.2.10 CREF10 – Adaptive Reduced-Rank Interference Suppression Based on the Multistage Wiener Filter

Abstract:

In this paper the authors propose a class of adaptive filtering algorithms for CDMA based systems and examine the performance. As result they show that such filters can show similar performance with a reduced rank as do conventional full-rank filters show.

Patent reference in Bibliography	CREF10
Restriction to a specific radar type	CDMA-based
Implementation effort	High
Side-effect with other methods	n/a
Mitigation effect on TX path	No
Mitigation effect on RX path	Yes
Computational effort	High
Interference mitigation category	Coding domain
Harmonization needed	t.b.d.
MOSARIM relevant	yes, if CDMA is relevant
Range of mitigation effect	t.b.d.

3.2.11 CREF11 – Airborne Radar Interference Suppression Using Adaptive Three-Dimension Techniques

Abstract:
In this thesis the authors propose an extension of state-of-the-art space-time adaptive processing (STAP). STAP helps to improve target detection in situations with interference. It involves a 2D filtering technique using a phased-array antenna with multiple spatial channels. The statistics of the interference environment is used to obtain a weight vector which then is processed together with the received radar signals.

Patent reference in Bibliography	CREF11
Restriction to a specific radar type	Phased-array
Implementation effort	High
Side-effect with other methods	n/a
Mitigation effect on TX path	No
Mitigation effect on RX path	Yes
Computational effort	High
Interference mitigation category	Space domain and time domain
Harmonization needed	No
MOSARIM relevant	No
Range of mitigation effect	t.b.d.

3.2.12 CREF12 – Combining raised cosine windowing and per tone equalization for RFI mitigation in DMT receivers

Abstract:
In this paper the authors propose a combination of raised cosine windowing and per tone equalization (PTEQ) for RFI mitigation in discrete multi-tone receivers (DMT). Discrete multitone offers an elegant way to achieve high capacity, dividing the spectrum into small bands and processing these individually. The per tone equalizer optimizes the capacity for each band individually, thus optimizing the whole. However, it provides little protection against narrow band radio frequency interference (RFI), being spread over all tones because of the high side lobes of the DFT filter bank used in the receiver. The use of windowing functions limits this noise spreading, but is difficult to combine with the PTEQ. This paper describes a method to combine the PTEQ with a raised cosine window, while keeping the complexity reasonable. Extensions to other windowing functions are also given.

Patent reference in Bibliography	CREF12
Restriction to a specific radar type	Radars using DFT technique
Implementation effort	medium

Side-effect with other methods	n/a
Mitigation effect on TX path	yes
Mitigation effect on RX path	yes
Computational effort	medium
Interference mitigation category	Frequency domain
Harmonization needed	t.b.d.
MOSARIM relevant	yes
Range of mitigation effect	t.b.d.

3.2.13 CREF13 – OFDM as a possible modulation technique for multimedia applications in the range of mm waves

Abstract:

OFDM (Orthogonal Frequency Division Multiplex) is a multiple carrier modulation technique with mainly use in the future mobile multimedia communications. OFDM is a wideband modulation scheme that is specifically able to cope with the problems of the multipath reception. This is achieved by transmitting many narrowband overlapping digital signals in parallel, inside one wide band. Increasing the number of parallel transmission channels reduces the data rate that each individual carrier must convey, and that lengthens the symbol period. As a result, the delay time of reflected waves is suppressed to within 1 symbol time. The influence of intersymbol interference is thereby significantly reduced.
OFDM can be simply defined as a form of multicarrier modulation where its carrier spacing is carefully selected so that each subcarrier is orthogonal to the other subcarriers. As is well known, orthogonal signals can be separated at the receiver by correlation techniques; hence, intersymbol interference among channels can be eliminated. Orthogonality can be achieved by carefully selecting carrier spacing, such as letting the carrier spacing be equal to the reciprocal of the useful symbol period.
Coded OFDM is more immune to impulse noise than single carrier system, because a coded OFDM signal is integrated over a long symbol period and the impact of impulse noise is much less than that for single carrier systems. The threshold level for the impulse noise, at which errors occur, can be as much as 11 dB higher than for a single carrier system.

Patent reference in Bibliography	CREF13
Restriction to a specific radar type	Only for OFDM modulated radar types
Implementation effort	High due to complex signal processing
Side-effect with other methods	unknown
Mitigation effect on TX path	yes
Mitigation effect on RX path	no
Computational effort	high
Interference mitigation category	Coding domain
Harmonization needed	no
MOSARIM relevant	To be clarified
Range of mitigation effect	11 dB for impulse noise

3.2.14 CREF14 – Listen before talk technique

Abstract:

Listen before talk technique is principally used in wireless ad-hoc networks with many transmitter units that communicate with an access point. In order to avoid collision of transmitted signals from two or more communication units each transceiver that wants to transmit a signal first scans its transmission channel whether it is already occupied by another signal transmission or free. Only in the case of a free transmission channel the unit will send

its message. For wired networks similar techniques exists like the automotive CAN bus that works with a recessive bit detection or the CSMA/CD (carrier sense multiple access with collision detection) which also senses the transmission medium, i.e. the copper cable or the fibre optic link, for already existing activity and only transmits if a free status was detected. With the LBT (listen before talk) technique almost interference free communication can be realized as long as the number of access attempt is low compared to the total channel capacity. When channel access attempts approach the full channel capacity, the number of signal interference increases exponentially and reaches full channel blockage when the units attempt to access the channel above its maximal capacity.
For a few automotive radars the LBT technique may be rather effective as long as each radar occupies the available bandwidth for a short time only. For safety-critical applications with real-time constraints LBT is less suitable.

Patent reference in Bibliography	CREF14
Restriction to a specific radar type	Not for continuous wave radar types
Implementation effort	medium effort for listen feature
Side-effect with other methods	unknown
Mitigation effect on TX path	yes
Mitigation effect on RX path	no
Computational effort	low
Interference mitigation category	Listen before talk
Harmonization needed	no
MOSARIM relevant	For non-safety application
Range of mitigation effect	Depending on sensor density; rather high for low density

3.2.15 CREF15 – Detect and avoid technology

Abstract:
Detect and avoid techniques mitigate interference potential by automatically switching to another frequency band to prevent a conflict with another signal. A conflict detection unit monitors the sound operation of the transmitting device and switches, in case that interference by another signal is detected, to another operational bandwidth or carrier. The change can be done randomly within the maximum allowed bandwidth and either by first scanning if the new selected bandwidth or carrier is free or not (see CREF 15) or by just jumping to the new operational values.
Sufficient available bandwidth is needed to make this DAA (Detect and Avoid) effective. At least a factor of 4 is recommended.

Patent reference in Bibliography	CREF15
Restriction to a specific radar type	Not for radars that occupy the whole allowed frequency band
Implementation effort	medium effort for detection feature
Side-effect with other methods	unknown
Mitigation effect on TX path	yes
Mitigation effect on RX path	no
Computational effort	low
Interference mitigation category	Detect and avoid (frequency domain)
Harmonization needed	no
MOSARIM relevant	yes
Range of mitigation effect	Depends on maximum allowed bandwidth to radar bandwidth ratio and radar device density

3.2.16 CREF16 – A Real Time Signal Processing for an Anti-collision Road Radar System

Abstract:
This method is based on a numerical correlation between the transmitted signal and the received signal. The signal uses orthogonal codes to ensure a multiple access communication between all vehicles in near area.
The studied anti-collision radar is based on spreading spectrum coded radar waveforms at 76-77 GHz and a numerical correlation receiver. The studied receiver computes the numerical cross-correlation between the received signal and a replica of the transmitted code to allow an optimal detection. The real time processing is tested in order to show their performances and disadvantages when applied to obstacles detection. The main idea is to achieve an efficient real time detection using a simple and low cost system..

Patent reference in Bibliography	CREF16
Restriction to a specific radar type	For pseudo random sequence radar
Implementation effort	medium effort for numerical correlation receiver
Side-effect with other methods	Can be combined with other methods
Mitigation effect on TX path	yes
Mitigation effect on RX path	yes
Computational effort	low
Interference mitigation category	Coding domain
Harmonization needed	no
MOSARIM relevant	possibly
Range of mitigation effect	t.b.d.

3.2.17 CREF17 – Hardware/Software Exploration for an Anti-collision Radar System

Abstract:
In this document the authors give estimation for needed FPGA hardware resources for two different correlation formulas.
The authors compare a simple mathematical correlation formula to a modified algorithm from Tugnait, named Higher Order Statistics (HOS) algorithm. There is a synthesis in which ways each algorithm can be calculated. The first result of this comparison is that there are different ways to calculate each algorithm with impact on the needed hardware resources of a FPGA. The second result is that the HOS algorithm leads to a better SNR and an increase of the maximum distance for the detection of obstacles. But this leads to an increase of hardware resources of the FPGA compared to the mathematical algorithm.
The authors simplified some steps of the algorithm to be able to implement this algorithm on the available resources of a chosen FPGA. This leads in a reduction of the performance of this algorithm. The validity of the reduced algorithm was proved by several test runs.

Patent reference in Bibliography	CREF17
Restriction to a specific radar type	No, can be used for any kind of vehicular radar
Implementation effort	maybe upgrade of FPGA
Side-effect with other methods	no
Mitigation effect on TX path	No
Mitigation effect on RX path	yes
Computational effort	high
Interference mitigation category	Coding domain
Harmonization needed	no
MOSARIM relevant	yes

Range of mitigation effect	5dB to 10dB

3.2.18 CREF18 – Conceptual design of a dual-use radar/communication system based on OFDM

Abstract:
It is a system which can be used interchangeably as a radar sensor and communication device based on OFDM architecture. Arbitrary waveform generator with high-speed DSP capabilities is being used to create either random or deterministic OFDM waveforms and a high-speed ADC board is used in the receiver's baseband portion to recover the incoming signals. OFDM technique is already widely used in broadband communications; however it is shown that system architecture based on this method of data coding and modulation can also be used in radar with minimum modifications. Indeed, modelling study shows that OFDM radar signals perform well in presence of jamming and interference and possess noise-like qualities making them good candidates for low probability of detect/intercept (LPI/LPD) system implementation.

Patent reference in Bibliography	CREF18
Restriction to a specific radar type	No, can be used for any kind of vehicular radar
Implementation effort	maybe upgrade of FPGA
Side-effect with other methods	no
Mitigation effect on TX path	No
Mitigation effect on RX path	yes
Computational effort	high
Interference mitigation category	Coding domain
Harmonization needed	no
MOSARIM relevant	yes
Range of mitigation effect	t.b.d.

3.2.19 CREF19 – Mutual Interference of Millimeter-Wave Radar Systems

The author of this document describes effects between two or more radar sensor for two different which leads to interference. First he described the interference between FMCW radars by an time-domain simulation model, later between Pulsed radars and at the end between Pulsed and FMCW radars.

These effects of FMCW radars can occur by the side lobes of the antenna, the shape of the target, the operating band and the sweep period and timing.
The author proposes to "use a narrow antenna beam that is physically scanned to minimize the probability of main lobe interference. The next proposal is to "use digital signal processing techniques to process the received signal either pre-FFT or post-FFT".
His third proposal is to "add jitter to both scan and sweep times to eliminate the possibility of coherence between the radar and the interference source.

The causing effects of interference between Pulsed radars are nearly similar to the FMCW radar according to the author. He proposes to control the pulsed amplitude at the receiving stage. The second suggest is integration by time transformation which leads to a decrease of the interfering amplitude up to 30dB. Because of that the magnitude of side lobe-coupled interference will be decreased to that below the noise floor.

His last proposal is to jitter the radar time base leads to a decrease of the possibility of coherence with an interfering source.

In the last part the author describes the interference between pulsed and FMCW radar. In the last part the author describes the interference between pulsed and FMCW radar. The influence from a pulsed radar on a FMCW radar "is easy eliminated by either clipping or masking out the offending pulse".
Because of different signal characteristics of the FMCW radar the disturbance on a pulsed radar "is not easily eliminated using the signal-processing techniques". It reduces the target SNR and ", hence, reduce the overall detection and target – tracking performance of the radar".

Patent reference in Bibliography	CREF19
Restriction to a specific radar type	Described for pulse and FMCW radar
Implementation effort	Design of antenna, additional code
Side-effect with other methods	Not mentioned
Mitigation effect on TX path	No
Mitigation effect on RX path	Yes
Computational effort	Additional code
Interference mitigation category	Time domain and space domain,
Harmonization needed	Not mentioned
MOSARIM relevant	Yes
Range of mitigation effect	10 to 30dB (depends on method)

3.2.20 CREF20 – SiGe Circuits for Spread Spectrum Automotive Radar

In this document the author describes a setup for transmit and receive stage based on SiGe circuits for a 79 GHz automotive radar sensor. The transmitter generates a pseudo noise (PN) sequence. This leads to avoidance of potential interference according to the author. The generator of this sequence consists of 10 stages of D Latches.

Patent reference in Bibliography	CREF20
Restriction to a specific radar type	Not mentioned
Implementation effort	Hardware implementation of PN sequence
Side-effect with other methods	Not mentioned
Mitigation effect on TX path	No
Mitigation effect on RX path	Yes
Computational effort	No additional effort
Interference mitigation category	Coding domain
Harmonization needed	Not mentioned
MOSARIM relevant	Yes
Range of mitigation effect	t.b.d.

3.2.21 CREF21 – Design and Demonstration of an Interference Suppressing Microwave Radiometer

Design and Demonstration of an Interference Suppressing Microwave Radiometer
In this article, a general RFI mitigation technique was used, called "Blanking". This technique is applied in the time domain and/or the frequency domain on the receiver side.
In the time domain variant, the (running) mean and the appropriate standard deviation are calculated. Then, a threshold is created out of this mean and standard deviation. This is done

by simply adding the mean and a not more specified multiple of the standard deviation together. If a signal goes over this threshold, the signal is regarded as an interferer. Then the interferer-signal-sample and a not more specified number of samples before and after this “interferer”-sample are set to zero. The length of this “set to zero block” should, ideally, include all multipath components of the interferer.
In the frequency domain variant, the mitigation is done for interferers mainly localized in frequency. The operation itself is named “cross-frequency” detection algorithm and is done by looking on a certain number of power spectra, which can also be averaged. The maximum is detected and compared with an expected power level of the use-signal. This algorithm is applied in the field of radiometry, so the threshold for the power level can be defined by taking the expected temperatures in the observed regions into account. Further, the distance in standard deviations from the mean is also used to create a threshold. If the signal gets out of the bounds of the defined thresholds, the signal-region is marked as interfered and is substituted by the sum of mean and standard deviation of the use-signal.

General comments: The time-domain-blanking strategy mitigates interference caused by huge power levels (e.g. from pulsed radars). The cross-frequency-blanking, in this version, is effective against CW interference [1-2]. But in both methods, the power level of the use-data has to be known and a not well defined number of samples before and after an interfered region loses all information.
Due to the fact, that the behavior of cars must be as causal as possible, a radar system cannot destroy signal information because of statistical abnormalities. Also, radiometry is, in general, not as time critical as automotive radars, so it can make use of comprehensive and complex detection methods with often relatively long integration times.

Further literature used:

[1] B. Güner, N. Niamsuwan, J.T. Johnson, “*Performance Study of a Cross-Frequency Detection Algorithm for Pulsed Sinusoidal RFI in Microwave Radiometry”,* IEEE transactions on geoscience and remote sensing

[2] B. Guner, J. T. Johnson, and N. Niamswaun, "Time and frequency blanking for radio frequency interference mitigation in microwave radiometry," IEEE TGRS, Nov 2007

Patent reference in Bibliography	CREF21
Restriction to a specific radar type	no
Implementation effort	low
Side-effect with other methods	no
Mitigation effect on TX path	no
Mitigation effect on RX path	yes
Computational effort	low
Interference mitigation category	Detect and repair (time domain, frequency domain)
Harmonization needed	n/a
MOSARIM relevant	No, because interference effects in the automotive field are changing relatively fast, in radiometry not.
Range of mitigation effect	Dependent on observing time

4 Summary and Outlook

This state-of-the-art report on interference mitigation techniques is focussed on implementation capabilities for use in vehicular radar applications and safety functions. The most promising ideas were found in a patent and conference paper survey and are compiled in a database. It is available on the web server and will be further analyzed, improved regarding the expected performance and combination capability and benchmarked in the simulation runs of WP 2 and WP 3.

The first coarse classification of the interference mitigation techniques in the six main categories (see chapter 2.1 to 2.6) helps to characterize and allocate the mitigation effects to their respective operational domain, i.e. polarization, time domain, frequency domain, code domain, space domain, strategic approaches, or a combination from all of these.

While some of the interference counteractions can be applied universally to all kind of radar systems, others can deploy their effects only for special radar types or configurations. Another important factor to consider is the range of the mitigation effect that can be achieved by the individual techniques and the needed implementation effort for it.

From the number of ideas found, the impression might be that there is only little room for new ideas and techniques. But derived from the first findings and results of this report it is already obvious for many collected techniques that with a single technique alone very safety critical applications can't be fully protected from harmful interference. Cascading several mitigation techniques to improve the robustness and susceptibility against other interferer may be a solution and has to be investigated.

Furthermore, relevant techniques need harmonization and cross-company cooperation in further developing them. Here, the MOSARIM consortium with the five main suppliers regarding automotive radar technology in Europe can significantly improve the situation by establishing a commonly developed and agreed benchmark regarding efficient vehicular radar mitigation techniques and providing the necessary prerequisites with respect to harmonization and other standardization issues.

The multitude of coding techniques and their importance regarding radar interference mitigation caused a more detailed description and analysis in Annex A. Compared to the radio-communication applications the full impact of coding techniques to radio-location (i.e. the vehicular radars) is less analyzed and explored yet. One of the MOSARIM project targets also is to improve this shortcoming with further contributions and results.

5 Annex A – Overview of different coding techniques

5.1 Interference mitigation considered as a multiple access situation

While the base problem studied (see for example [Bro07]) could be considered strictly as interference mitigation, more insight can be gained by considering this problem as a multiple access problem: all users share the same resource: the ACC and SRR allocated frequency bands with the associated emission power (limited by regulations). Ideally, each user shall be able to make use of all the available bandwidth and emission power without adverse effects to other users, in situation such as the one illustrated in Figure 2.

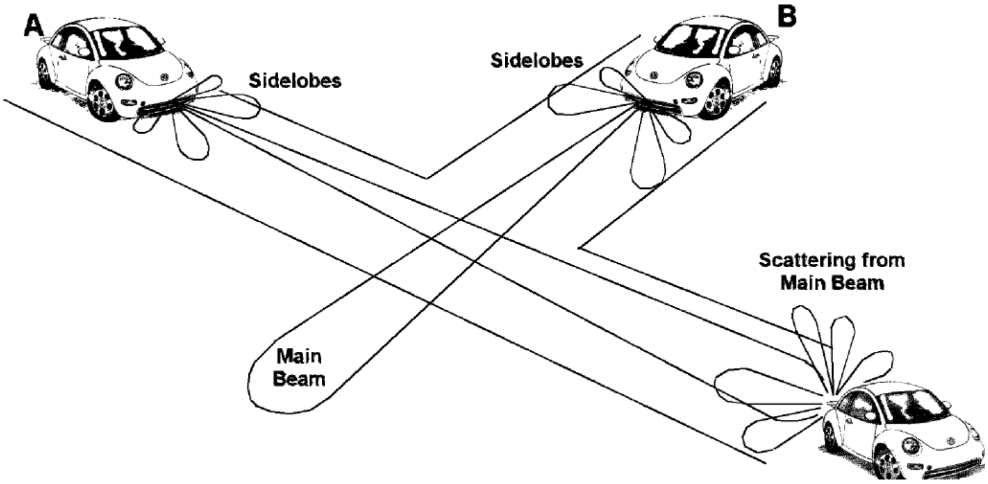


Figure 2 - Example of a multiple access situation.
Excerpt from [Bro07].

In the next section, the main approaches for multiple accesses used in telecommunications systems will be presented, and their relevance to the automotive radar application will be briefly discussed.

5.2 Desired properties for a multiple access automotive radar

In order to focus the study, some desired properties for automotive radars are summarized in Table 1.

Table 1 – Desired properties for a multiple access automotive radar system

Property	Desired value	Comments
Unambiguous range	$R_{max} > 200$m	
Range accuracy	$\Delta R < 0.5$ m	Required for precise target tracking
Velocity accuracy	$\Delta V < 1$ km/h	Required for precise target tracking
Number of concurrent users	> 10	The simultaneous presence of more users at the same location should be rare
Refresh time	< 50-100 ms	Shorter refresh times are desirable
Data rate	< 100 Mbit/s	Higher data rates require expensive interfaces
Interferer rejection	> 60 dB	High rejection is required in adverse situations

Concerning the requirement on interferer rejection, Brooker [Bro07] notes that:

> "The potential interference level by an automotive radar at 200 m in clear air is about 56 dB higher than the return from a 1 m^2 target at the same range." [Bro07]

This explains why the interferer rejection must be as high as 60 dB. In many situations where a desired target does not come in concurrence with the interferer, lower rejections values could be accepted.

5.3 Multiple access approaches

In telecommunications systems, multiple access systems have been extensively studied and are currently employed in various systems having a large user base. In the following section, the basic approaches to multiple access in narrowband systems will be briefly presented. The most relevant approaches to simultaneous radar operations (broadband) will be selected and analyzed in greater detail.

5.3.1 Overview of multiple access approaches for narrowband signal

At the crudest detail level, four main techniques for multiple access in systems using narrowband signals can be distinguished: [HT02, OR98]

- **SDMA**: **S**pace **D**ivision **M**ultiple **A**ccess: in this approach, the shared resource is divided in spatial zone where no sharing occurs. This technique (among others) is used for example in GSM telephony. In the context of this study, this technique cannot be applied: the motivation for this study is to remedy to possible adverse interferences occurring when automobile carried radar devices are employed in close vicinity to each other (see for example Figure 2).
- **TDMA**: **T**ime **D**ivision **M**ultiple **A**ccess: in this approach, the shared resource is divided in short time intervals. During any time interval, only one system is allowed to use the resource. Several automotive radar systems would for example be required to perform their measurements sequentially. Again, in the context considered in MOSARIM, this approach seems poorly fitted: the measurement time for each device is reduced (this reduction grows linearly with the number of devices being used simultaneously). Moreover, this technique requires all systems to be synchronized. Typically, this synchronization implies the existence of a communication link between all systems sharing a resource. Although joint radar/communications systems have been proposed [SSW07, SRZW09, SZW09], the synchronization requirement is expected to be difficult to satisfy in practical systems. Moreover, since TDMA reduces the perceived availability of the resource for each user, it is not considered among the most promising approaches for a multiple access automotive radar application.
- **FDMA**: **F**requency **D**ivision **M**ultiple **A**ccess: in this approach, the bandwidth resource is divided in non-interfering, narrower sub-bands. Each user is restricted to operating within his respective sub-band. FDMA encoding is schematically illustrated in Figure 3(top). Advanced techniques such as OFDM (Orthogonal Frequency Division Multiplexing) enables users to use closely spaced sub-bands. When OFDM is combined with the CDMA approach, each user is able to use a set of narrow band signals, possibly spread across a wide band of frequencies. ODFM encoding of automotive radar signals has been demonstrated at 24 GHz [SSW07, SRZW09].

- **CDMA**: **C**ode **D**ivision **M**ultiple **A**ccess: in this approach, the useful signal is also spread onto a broader spectrum, but the spreading is done according to a device specific code. The decoder is tuned to a specific code. Since codes are designed to have a very high autocorrelation but a very low cross-correlation, the decoder is able to recover the coded signal while other sources are blocked. CDMA encoding is schematically illustrated in Figure 3(bottom).

Considering MOSARIM's intended goal, which is to enable the independent operation of various automotive driver assistance radars, the SDMA and TDMA approaches seem poorly fitted to the task. In comparison, spread-spectrum approaches, i.e. FDMA and CDMA, are recognized as attractive candidates for the type of operation considered.

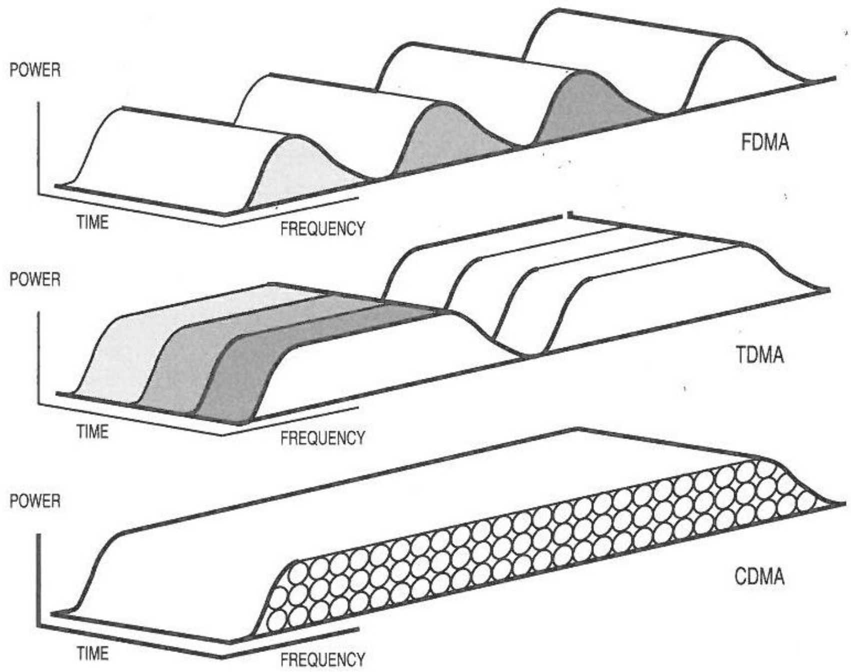


Figure 3 - Schematic comparison of 3 multiple access approaches: Frequency Division Multiple Access (FDMA)(top), Time Division Multiple Access (TDMA) (bottom), Code Division Multiple Access (CDMA) (down). Excerpt from [HT02].

5.3.2 Applicability of the FDMA approach:

Brooker [Bro07] studied some aspects concerning the expected performance of the FDMA approach applied to automotive collision avoidance. In particular, the case of a 2 GHz allocated band is considered. The FDMA approach is used to split this resource in 10 sub-bands of width 200MHz. This would result in a range resolution close to 0.75m for a short range radar system. As much as 10 simultaneous users could be supported in such a system.
Brooker inspected many possible configurations where interference will occur and concludes:

> "Whether this interference will be interpreted as a target vehicle or a roadside obstacle will depend on the similarities between the characteristics of the two radars and their relative timing. It has also shown by means of simulation and confirmed using measurements on a 94-GHz FMCW radar system that in most cases, the effect of the interference (between two FMCW radars) will result in a

significant and continuous decrease in the available SNR and that the form of the interference is not amenable to elimination using simple signal-processing techniques." [Bro07]

Based on this example, we can conclude that using frequency division multiple access in automotive radar systems will lead to limited range accuracy (not better than 0.75m), even if only a limited number of users is considered. Moreover, a successful implementation of the FDMA approach would require the development and testing of algorithms for detecting possible collisions. Collisions would occur when two radars that are using the same sub-band come into the vicinity of each other. The collision avoidance algorithm should be able to reliably detect the frequency collision (based on the perturbations caused by interference), so that one of the radar devices can be switched to an alternate operating frequency.
One key advantage of the FDMA approach is that it could be applied with little or no change to existing radar hardware. Only newer radar devices would be required to have the frequency agility required to hop to another operating frequency when a collision in the band is detected. The main obstacles to the FDMA approach are the implied limitation to the radar accuracy (caused by the need to split the total available bandwidth), and the possibly high overhead for algorithms used in reliable identification of frequency collisions. Moreover, the frequency agility required to avoid collisions can be leveraged more efficiently in frequency-hopping systems (discussed in section 5.4.2).

5.3.3 Illustrative applications of CDMA

The CDMA approach can have multiple expressions, as illustrated schematically in Figure 2.4.1.1.

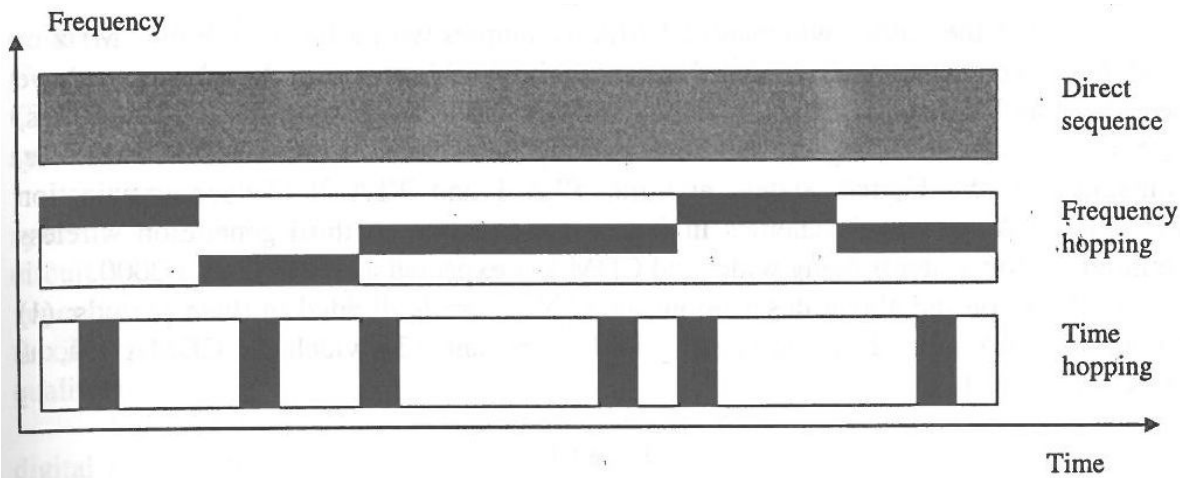


Figure 4 - Schematic representation of 3 approaches to CDMA
Excerpt from [OR98]

- Direct-sequence (DS-) CDMA implies a direct coding of the bit stream transmitted by the emitter. In telecommunications, this technique is used is used for example in GPS and Galileo navigation devices, as well in Wi-Fi systems (IEEE802.11b). It is also referred to as DSSS (Direct Sequence Spread Spectrum).
- In frequency-hoping spread spectrum (FHSS), the code is used to determine the width of frequency jumps which are performed at a constant repetition rate. This technique requires frequency agile modulation and demodulation. It is used for example in the Bluetooth protocol.
- In time-hoping spread spectrum, the amplitude of the transmitted signal is modulated in time intervals given by the code. This type of technique is used in systems having a

high temporal resolution. Such systems include ultra wideband (UWB) systems (discussed below).

- In multiple-carrier (MC-) CDMA (not illustrated), each user is allowed to transmit simultaneously on multiple subcarriers, the frequency spacing between the subcarriers being given by the code. The orthogonal frequency division multiple access (OFDMA) approach can be considered as a specific case of MC-CDMA. It is used in the IEEE 802.16 WiMax standard.

Note that the multiple access property observed in CDMA systems is due to the interference rejection properties of the code. Typical codes used in CDMA systems include MLS: Maximal Length Sequences, sometimes referred to a M-sequences, and the more complex Gold codes, which have generally lower cross-correlation than same length MLS.
As a practical rule, it can be noted that the quality of interference rejection grows with the code length M: longer codes allow for more efficient rejection. According to [Lin95], 1023 bits long codes allow for 12 dB of interferer rejection, while 60 dB of rejection would require using codes with length 2^{45}.

5.4 Applications of multiple access telecommunication techniques to automotive radar

Generally speaking, radar systems can be considered at physical layer as telecommunication systems with the following differences:

- For radars, the emitter and receiver are located in the same place.
- The receiver knows the "data" emitted (waveform in the case of radar). The only purpose is the estimation of time delays and frequency shifts.
- Usual bandwidths of modulated signals are very different (typically 10 or 20 MHz for telecommunication systems and 1 GHz for radars).
- The regulated EIRP is comparable for radars (-3 dBm/MHz) and telecommunication systems in ISM free bands (for example 1.5 dBm/MHz for WiFi in 5 GHz band).

This section shows how to apply relevant multiple-access techniques to the domain of automotive radars.

5.4.1 Applications of DS-CDMA to automotive radar

This approach requires applying a binary modulation to the amplitude or the phase of the emitted RF signal. The demodulation is typically done by correlation of the received signal by the emitted signal. Automotive radars of this type are often referred to as 'noise radars'.
A schematic representation of a noise radar based on 1023 bits long pseudo-noise codes is provided in Figure 5 [FB00].

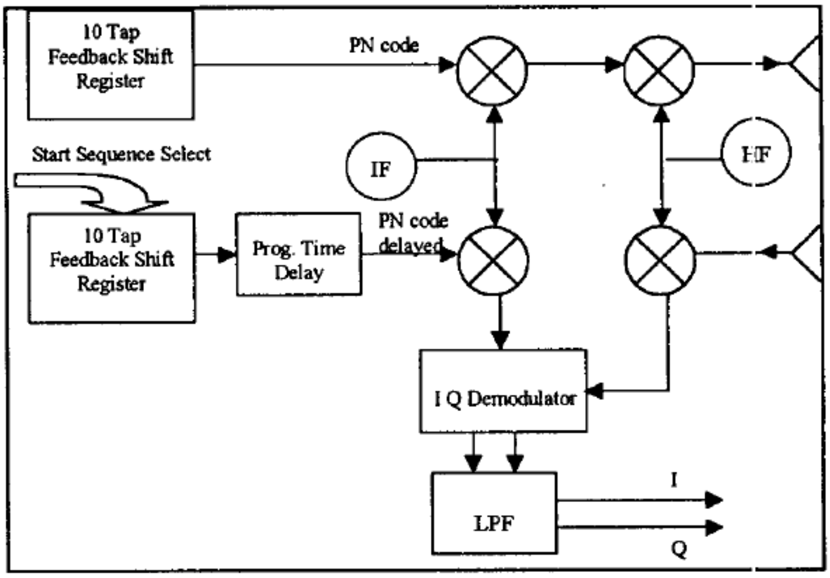


Figure 5 – Block diagram of a pseudo-noise radar

Excerpt from [FB00] – The 10-tap feedback register allow to produce pseudo-noise M-sequence codes of length 1023. The code clock rate must be set low enough so that the generated noise signal stays within the bounds of the IF bandwidth.

Pseudo-noise sequences generated by feedback shift register are often used in telecommunications since they are cheap to produce, both on the emitter and the receiver. The bandwidth of the noise can then be adapted to the intended applications, by changing the clock rate. In radar systems, a true random noise source can be used, provided that its bandwidth B is adapted to the desired range resolution ($\Delta R = c/2B$).

The modulation chosen is typically Binary Phase Shift Keying (BPSK). The bandwidth of the modulation is typically can go from 50 MHz to more than 2 GHz in recent systems, as summarized in Table 2:

Table 2 – Comparison of a selection published articles on CW noise radars

Ref	Carrier [GHz]	Noise bandwidth [MHz]	Code length [bits]	Range resolution
[SDE+06]	76.5	**68**	127	
[JHGSHWM01]	77	**128**	127	
[LMA+01]	76.5	**180**		
[FB00]	24	**450**	1023	33 cm
[TDK+07]	79	**1235**	1023	12 cm
[FNU+07]	26.4	**2.5**	2047	

One of the main disadvantages of noise radar is the requirement for high IF frequency circuitry in order to correctly demodulate the large bandwidth noise signals. Moreover, the noise sequence used in these radars appears to be exclusively M-sequences (most probably chosen for their good auto-correlation properties). Enabling multiple access will require to use longer codes, with low cross-correlation.

Efficient implementations of correlation algorithms required for the demodulation of DS-CDMA M-sequence waveforms are studied as a part of the ModEasy project (http://www2.lifl.fr/modeasy/) [LBGMA+06, ZRN+07].

5.4.2 Applications of FHSS to automotive radar

Mu *et al* [MXMJ09] consider a simple modification to the linear frequency modulation continuous wave (LFMCW) approach to allow for multiple access. Using as a basis the a double triangular waveform proposed by [RM01], which is adapted for multiple target situations, multiple access is enabled through a repetition of the basis waveform with frequency-hops given by a pseudo-noise M-sequence, as illustrated in Figure 6.
Unfortunately, this approach, which would require very little change to existing LFMCW radar hardware, and seems promising in simulation results, requires measurement times which are too long to be practical: each chirp is 2 ms long, so that the basis waveform is 8 ms long, and Mu *et al* state that at least 512 repetitions of the basis waveform are required to ensure good interference rejection. The obtained radar system would have a refresh rate of only 0.25 frames per second, whereas the requirement would be 10 to 20 frames per second.

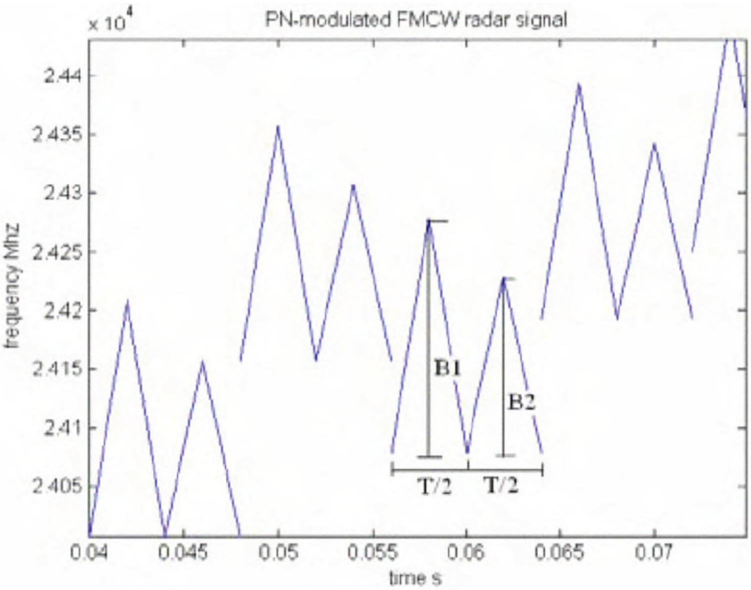


Figure 6 - Frequency-hopping spread spectrum applied to FMCW modulation

Excerpt from [MXMJ09] – Two triangular waveforms with different bandwidth are juxtaposed in order to reduce ambiguities in situation with multiple targets. The hopping frequency jump is a multiple of the maximum expected beating frequency f_b. While only 4 frequency hops are illustrated, at least 512 similar hops are employed to reduce the interference between different bandwidth users.

In order to apply the frequency hopping in practical radar systems, the linearity must be left out of FMCW systems. The LFM-FSK waveform proposed by Rohling *et al* [RM01] used two intertwined chirp signals to reduce ambiguities in situations with multiple targets. In a similar fashion, replacing the linear chirp by a series of small burst whose succession is not linear anymore, but given by a noise-like code allows to reduce the cross correlation between different users. This type of modulation is used for example to separate signals emitted by MIMO antennas [CV08]. An illustration of this frequency hopping approach is provided by Garmatyuk [GS08]: see Figure 7, centre column.

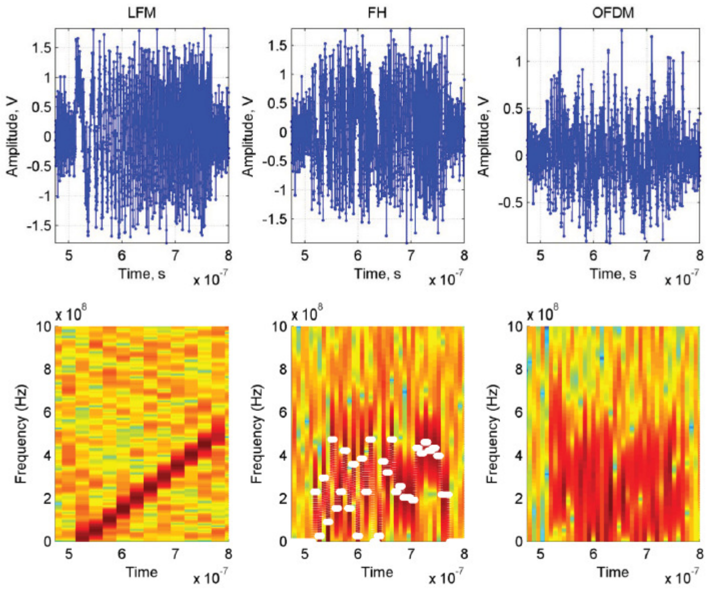


Figure 3. Time-domain views of LFM, FH and OFDM signals in noise and their respective spectrograms

Figure 7 – Comparison of the spectrograms of LFM, frequency hopping and OFDM signals

Excerpt from [GS08] – In the LFM signals, the frequency components increase linearly with time. In frequency-hopping modulation, the succession of the frequency components is given by a pseudo-random code. In OFDM, multiple frequencies are transmitted at the same time.

Practical measurements from radars using frequency-hopping waveforms are scarce for systems similar to automotive radars. This can be partially explained by the fact that frequency hopping radars have been primarily proposed for military applications. In 1999, Sanmartin-Jara *et al* [SJBGRS99] proposed a frequency-hopping waveform with a 128 bit code, spanning 100MHz. Good autocorrelation results were found in simulation, but no results for cross-correlation performance were provided. Axelsson proposed a “random step frequency radar” [Axe07]; while the implementation presented used a 5.65 GHz carrier frequency, the same methodology can be applied for radars at automotive frequencies. The real world data used in Axelsson’s experiment was acquired with a standard stepped LFMCW radar, and re-ordered to simulate the stepped frequency waveform. The radar bandwidth spanned approximately 10 GHz, and 2000 element long code sequence were used. One of Axelsson’s observations is that random frequency steps lead to a higher noise floor. Such adverse effects are expected, and can not be cancelled in systems aiming for multiple access.
In terms of RF hardware, using random frequency hops over a wide band (B > 500 MHz) might be challenging. Future research could be focused on codes providing acceptable autocorrelation and cross-correlation properties while conforming to present technology constraints for changes in the VCO frequency.

5.4.3 Applications of Ultra-Wide Band (UWB) to automotive radar

The definition of ultra-wideband is not consistent. The US-administration FCC (Federal Communications Commission) defines systems as ultra-wideband if the used bandwidth B, defined as the -10dB spectral band around the carrier frequency f_c, is equal or greater than 500MHz, or 20 percent of f_c [FCC02]. In Europe however the definition of UWB is different. Here a device is called UWB if it uses more than 50 MHz bandwidth. Ultra-wideband technology uses different modulation schemes as described in ETSI EN 302288 and TR 102 664. One example is a system using very short pulses to spread the spectrum of the transmitted signal over several gigahertz. In telecommunications, UWB is typically employed for short range data links, which are prohibited from interfering with existing telecommunications infrastructures (such as cell phone networks). The energy of a UWB

signal is spread over a broad spectrum, so that interference with existing narrowband systems becomes negligible.
Since UWB relies on ultra-short pulses, employing time-hopping CDMA techniques comes at very low additional cost: each pulse can be considered as a ‘chip’ in a code sequence (a chip in a binary code is the elementary code element: in this case: the presence of a pulse or its absence). Such pulse sequences are illustrated for example in Figure 8. In the pulse UWB, it is advantageous to use sparse code sequence, as is done in [MKR07], since this limits the total power radiated by the radar system during its operation.

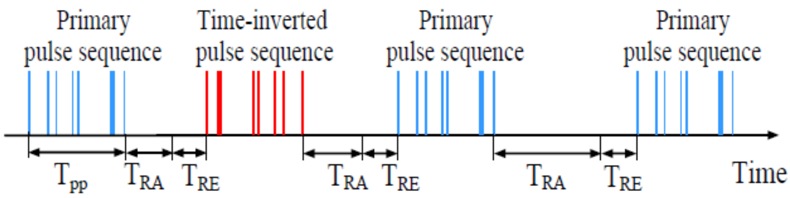


Figure 8 – Structure of a time-hopping pulse train

Excerpt from [MKR07] – In this pulse train, the primary sequence is composed by 10 pulses. However, to enhance interferer rejection, the primary pulse sequence is repeated hundreds of times at regular intervals.

In the PRIMA-CARE project, sponsored by the French ANR (https://prima-care.inrets.fr), UWB waveforms with CDMA modulation based on Gold code and M-sequences were tested with a prototype radar: [SDE+06, SER+07, SEZ+09, SRB+09, STB+08, ZRN+07]. Experiments confirmed that the M-sequences perform best in terms of auto-correlation. However, if the focus is set to multiple access (i.e. low cross-correlation), Gold codes outperform M-sequences.

5.4.4 Applications of MC-CDMA to automotive radar

An illustration of the MC-CDMA approach is provided in Figure 7, last column [GS08], where it is labelled as OFDM. Orthogonal frequency division multiplexing is a specific case of MC-CDMA, where the spacing between the subcarriers in the band is minimal, while still allowing for separation of each sub-band. In Figure 7, 128 sub-bands are used.
OFDM is currently being deployed in many communications systems requiring high bandwidth. Therefore, several proposals point to the convergence of radar and inter vehicle communications. See for example [vG09] for a recent overview.

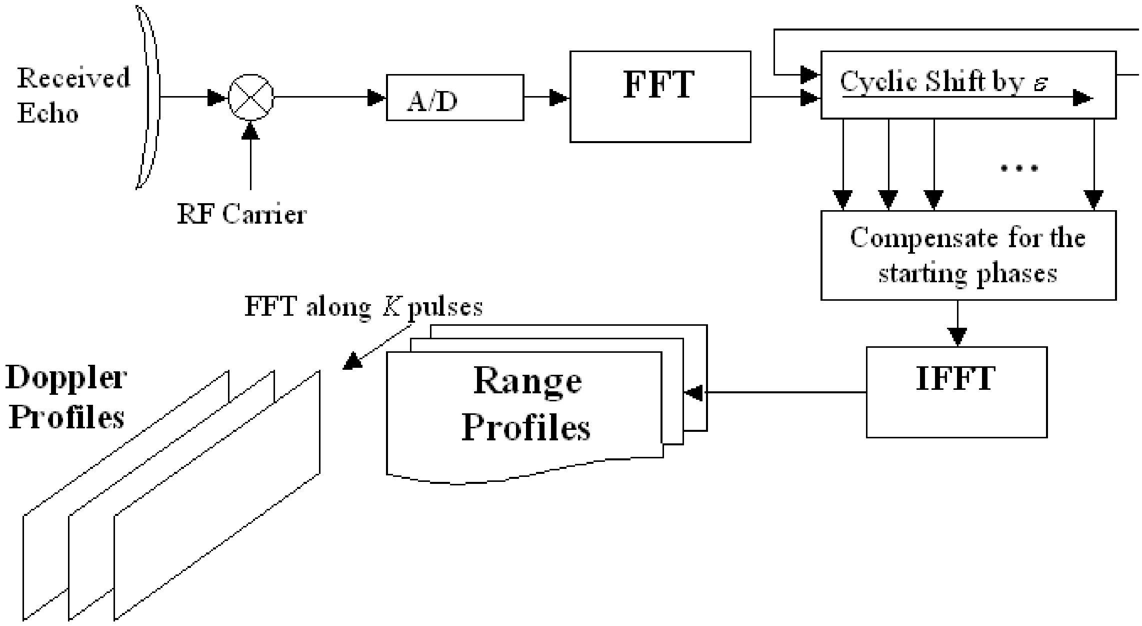


Figure 9 – Block diagram of the processing scheme for OFDM radar

Excerpt from [TdHvG09] – In OFDM, the demodulation of the coded received signal is done in the digital domain immediately after the RF carrier removal. This requires a very high rate A/D converter, but offers great flexibility in terms of decoding options (albeit at a high processing cost).

However, OFDM radars have hardware requirements difficult to meet at a reasonable cost in current technology. The processing is done exclusively in the digital domain; therefore, a high sampling rate analog-to-digital converter must be employed immediately after RF carrier removal. Van Genderen *et al* [vG09, TdHvG09] uses an expensive Agilent arbitrary waveform generator to produce 300 MHz bandwidth OFDM pulses with 300’000 sub-bands, and attains peak-to-side-lobe levels (PSLL) of 60 dB. Using currently of the shelf components, and the same bandwidth of 300 MHz, Garmatyuk *et al.* [GS08] needed a 600 Ms/s ADC and FPGA.

Since the high A/D conversion rate in OFDM expensive, conventional MC-CDMA approaches with less closely spaced multiple carriers could be attractive. However, multiple RF carriers require that presence of multiple RF oscillators in the transmission and reception circuitry, which also have a significant impact on device cost.

These reasons indicate that OFDM radar is not a preferred candidate for large volume applications such as automotive radars. However, this restriction could be lifted in the future if the price of high frequency embedded digital processing becomes lower, or if the additional inter-vehicle communication capability offered by OFDM is considered as sufficient to justify the price difference.

5.5 Conclusions

We have seen that CDMA seems the most promising approach for multiple access radar systems. In order to achieve better rejection of interferers, long codes should be employed. Ideally, the interference rejection should be greater than 60 dB. Typical codes currently employed are maximum length sequences, which can be generated cheaply and have good auto-correlation properties. If multiple access is a priority, Gold codes should be used, since their cross-correlation is lower than same length MLS.

Evolution paths towards multiple access have been identified for the major types of currently available automotive radars. For continuous wave noise radars, which are already using DS-

CDMA, the only changes required are longer codes, and using codes with low cross-correlation. For existing linear FMCW systems, the codes can be used to define a stepped, frequency-hopping waveform. For pulsed radar systems, time-hopping waveforms are most appropriate. Finally, the MC-CDMA (OFDM) approach could also be considered, since it permits a very efficient use of the allocated bandwidth. Unfortunately, the demodulation requires sampling the received signal at a very high rate, so that this option does not currently provide the best cost-efficiency, but remains valid if the inter-vehicle communications must be combined with the radar functions.

5.5.1 Future steps

Further investigation of interference mitigation in automotive designs could be focused on assessing the performance of codes specifically designed for CDMA in typical automotive scenarios. In particular, specific sets of low cross correlation sets could be determined, for a restricted number of radar architectures, and their performance compared to industry standard modulation techniques, both in situations with low interference, and in situations with a large number of interferers (between 5 and 10).
The first selected radar architecture is the FMCW radar, where linear frequency modulation will be compared to frequency-hopping using Gold codes. Then, time permitting, a similar set of simulations could be performed for DS-CDMA noise radar, where M-sequences will be compared to Gold codes.
In both cases, the optimal code length will have to be determined, based on realistic hypotheses for the frequency hop bandwidth and settling time in FMCW systems, or the available modulation rate used in DS-CDMA systems. Moreover, simulations with large numbers of interferers will allow characterizing the response of a target system to different levels of interference. In adverse situations where the interferer power is significantly larger than the power returned from real targets, coding techniques could fail to totally reject the interference. In that case, the observations made about the interference failures modes of radars architectures studied will prove useful to generate an alert about the strong jamming, which could then be relayed to a driver assistance system, or the driver himself for further diagnostic or action.

6 Bibliography

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Inventors: Yuu Watanabe (JP), Kazuma Natsume (JP)

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Inventors: T. Mc Evan (US)

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Inventors: Fumihiko Okai (JP), Hiroshi Kuroda (JP)

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Inventors: Wieslaw Szajnowski (GB), (JP)

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Inventors: Jen King Jao (JP)

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Inventors: Russel.F.Sherry, San Diego; Jerry D. Woll, Poway; Van R. Malan, La Jolla, all of Calif.

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Inventor: Wolfgang Rebhan

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