EUROPEAN COMMISSION
Community Research

## Contract no.: 248231

# MOre Safety for All by Radar Interference Mitigation

# D5.2 – Guidelines to reduce mutual interference effects and to cope with interference cases

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|---|---|
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SEVENTH FRAMEWORK PROGRAMME

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## Revision chart and history log

| Version | Date | Reason |
| --- | --- | --- |
| 0.1 | 19.09.2012 | Initial version |
| 0.2 | 24.09.2012 | Document structure to handle D5.2 and D5.3 in parallel (same chapters, but for different functions with lower/higher requirements |
| 0.3 | 15.11.2012 | First draft version |
| 0.4 | 20.11.2012 | Updated version |
| 0.5 | 28.11.2012 | Further edits and text |
| 0.6 | 29.11.2012 | New contributions |
| 0.7 | 30.11.2012 | Preparation version for peer review |
| 0.8 | 30.11.2012 | Version for peer review |
| 0.9 | 04.12.2012 | Update with the peer review comments |
| 1.0 | 06.12.2012 | Final version for submission |

SEVENTH FRAMEWORK PROGRAMME

# Table of content

# 1. Executive summary

In this deliverable, information and knowledge that was gathered during the course of the MOSARIM project is collected in guidelines for the different mitigation techniques. The impact on sensor design and operational parameters and the expected mitigation margin of a specific countermeasure is described and the applicability for the different modulation schemes processed.
These guidelines should be seen as a first step towards globally available and harmonized standards that will help to reduce the interference risk to a minimum or even suppress it completely. This is of imminent importance for the near future when radar proliferation and roll-out will have reached a level that every new car is equipped with at least one radar sensor.
All the findings and results in this document are either validated or cross-checked by real world measurements and tests or/and by simulation means.

**General remark:**
The complexity of radar interference is too high to come up with already final conclusions, guidelines or even fully elaborated standards on how the interference risk can be best counteracted. The results and findings reported in this document are, however, a good basis and starting point to evolve towards the future aim – a globally available and harmonized standardization on radar interference mitigation.
As mitigation techniques are not specific for the investigated automotive applications, the Deliverables 5.2 and 5.3 are consequently treated in common.

# 2. Introduction

From the Description of Work (DoW), Deliverable 5.2 should address applications with lower requirements while Deliverable 5.3 should cope with functions having higher requirements.

However, from the perspective of mitigation techniques it was found that this doesn't play any role at all. That means, from technical content the two deliverables are absolutely identical. This fact was not apparent at the time the DoW was written and ultimately one deliverable would have been sufficient in that case.
Nevertheless, to keep conformity to the DoW and the deliverables that are due, this document, developed and written jointly by the two task leaders Bosch and Continental, will be submitted individually as foreseen. Reading only one of the documents is sufficient as the content is absolutely identical.

Regarding the different wordings in the headlines of Deliverable 5.2 ("guidelines") and 5.3 ("recommendations") the MOSARIM consortium concluded that for both deliverables the word "guideline" is used. This selection was made having the following ranking in mind (given in ascending order):

Guideline ->Recommendation -> Directive -> Decision -> Standard -> Rule -> Law

By defining "only" guidelines the character and consequences of that what is written in this document is well met. The hints and opinions stated with respect to mutual radar interference mitigation are merely on an advisory level and lack any right for mandatory or regulatory implementation. Indeed, radar interference countermeasures are deemed to be not implemented on a compulsory level. The MOSARIM consortium sees these guidelines more in the sense of a self-commitment to contribute to a minimum or even interference-free radar operation. Possible ideas and ways forward on how to disseminate and implement the results of this report are not within the planned task of the MOSARIM project and may become a subject in a future research program. The non mandatory approach does however not mean that neither precise standards nor harmonised regulations are needed.

All the experience that was gathered within the MOSARIM project to cope with and mitigate as much as possible mutual radar interference will be documented in the following chapters. Where no practical experience was gained, simulation results will contribute to setup the guidelines, respectively.

In chapter 3 the driver assistant functions with lower and higher requirements are addressed and the general project findings recapitulated.

In chapter 4 guidelines regarding the implementation of different mitigation techniques, as listed in chapter 3, are given. For each mitigation technique a set of hints is given. This set reflects some key points for decision w.r.t. sensor design and implementation form. It should be noted here that due to the individual design of the target system the applicability or the wanted mitigation effect is difficult to be guaranteed under all circumstances. This holds fully true for mitigation techniques operating on the transmitter (Tx) side, where coordination and harmonization is a must.

In chapter 5 a few validation checks with the simulation tool-chain for some of the mitigation methods are shown.

In chapter 6 the challenge to create a checklist is addressed.

The document will close in chapter 7 with conclusions and an outlook to further work that can be done in the same context.

# 3. Driver assistant functions with lower [or higher] requirements and impact on the mitigation margin

In Deliverable 5.1 [D5.1], a differentiation in safety functions with lower requirements (commonly named comfort functions) and with higher requirements (so-called safety functions) was already addressed and described for various different automotive applications. Furthermore, it was considered, whether mitigation techniques because of their principle of operation are not suited for certain radar applications (see Table 1).

| MITIGATION TECHNIQUES | | Adaptive cruise control | Collision Warning System | Collision Mitigation System | Vulnerable road user detection | Blind Spot Monitoring | Lane Change Assistance | Rear crossed traffic alert | Back-up Parking Assist |
|---|---|---|---|---|---|---|---|---|---|
| | Safety requirement is mainly -> | high | low | high | high | low | low | low | high |
| | Function impact level -> | active control | driver warning | active control | active control | driver warning | driver warning | driver warning | active control |
| T3.1 | CFAR (constant false alarm rate) for interference mitigation | usable | usable | usable | usable | usable | usable | usable | usable |
| T6.5 | Detect interference and change transmit frequency range of chirps | limited (24 GHz) usable (77/79 GHz) | limited (24 GHz) usable (77/79 GHz) | limited (24 GHz) usable (77/79 GHz) | limited (24 GHz) usable (77/79 GHz) | limited (24 GHz) usable (77/79 GHz) | limited (24 GHz) usable (77/79 GHz) | limited (24 GHz) usable (77/79 GHz) | limited (24 GHz) usable (77/79 GHz) |
| T2.1 | Using pauses of random length between chirps or pulses | limited | limited | limited | limited | usable | usable | usable | usable |
| T3.4 | Application of driving direction specific pre-defined frequency band separation | limited (24 GHz) usable (77/79 GHz) | limited (24 GHz) usable (77/79 GHz) | limited (24 GHz) usable (77/79 GHz) | limited (24 GHz) usable (77/79 GHz) | limited (24 GHz) usable (77/79 GHz) | limited (24 GHz) usable (77/79 GHz) | limited (24 GHz) usable (77/79 GHz) | limited (24 GHz) usable (77/79 GHz) |
| T6.2 | Detect interference and repair Rx results (Time domain) | usable | usable | usable | usable | usable | usable | usable | usable |
| T2.2 | Using random sequence of chirp types (Up-chirp, Down-chirp, CW-Chirp) | usable | usable | usable | usable | usable | usable | usable | usable |
| T5.4 | Digital Beam Forming | usable | usable | usable | usable | usable | usable | usable | usable |
| T6.4 | Detect interference and change timing of transmit chirp or pulses | usable | usable | usable | usable | usable | usable | usable | usable |
| T1.2 | Specific polarisation following the Radar location (frontal, rear, side) | usable | usable | usable | usable | usable | usable | usable | usable |

Tested within MOSARIM (real measurements)

Not Tested within MOSARIM (Only estimation or simulation)

**Table 1: Overview of different mitigation techniques w.r.t. safety requirement, function impact level and application (source: [D5.1]-Table 5). Individual mitigation margin is not considered.**

The borderline between functions with low requirements and high requirements is drawn, as shown in Table 1, depending on the activity and impact level of the respective function. As long as only informative actions like warnings or other possible driver alerts are taken into account, the case of low requirement (QM according to ISO26262) is assumed. For automotive functions with direct access to any active vehicle control like steering or braking a higher requirement level (from ASIL A to ASIL D according to ISO26262) is expected. This definition is common understanding in the automotive safety integrity level (ASIL) community.

In deliverable D1.4 the ASIL aspects were addressed and failure in time (FIT) limits for E/E architecture were given [D1.4]. Relationships and formula to calculate or derive the FIT rate for interference over victim receiver noise level (I/N) were also provided. However, as no information or guideline was available how to deduce the newly in MOSARIM introduced “FIT rate for interference” from the already existing E/E architecture FIT limits, no absolute FIT value for interference could be calculated. Nevertheless, on a qualitative level it can be stated that the higher the safety requirements are, the lower the interference to noise level should be.

As a matter of fact it turns out that the differentiation between driver assistant functions with lower or higher requirements can be directly mapped to a needed mitigation margin, that is lower for assistant functions with lower requirements and vice versa.
Defining a necessary mitigation margin value (under the precondition of a maximum possible interference power) depends on the ASIL level of the respective application. Up to now the ISO 26262 working group has not defined any ASIL level for the eight driver assistant functions addressed by MOSARIM. Furthermore, the different ASIL levels FIT rates are only defined for E/E architecture failure and no indication is given which portion of the FIT rates for E/E failure can be used for the interference case.
With this lack of information only a first qualitative “guess” for the interference specific safety requirements can be given, as sketched in Figure 1.

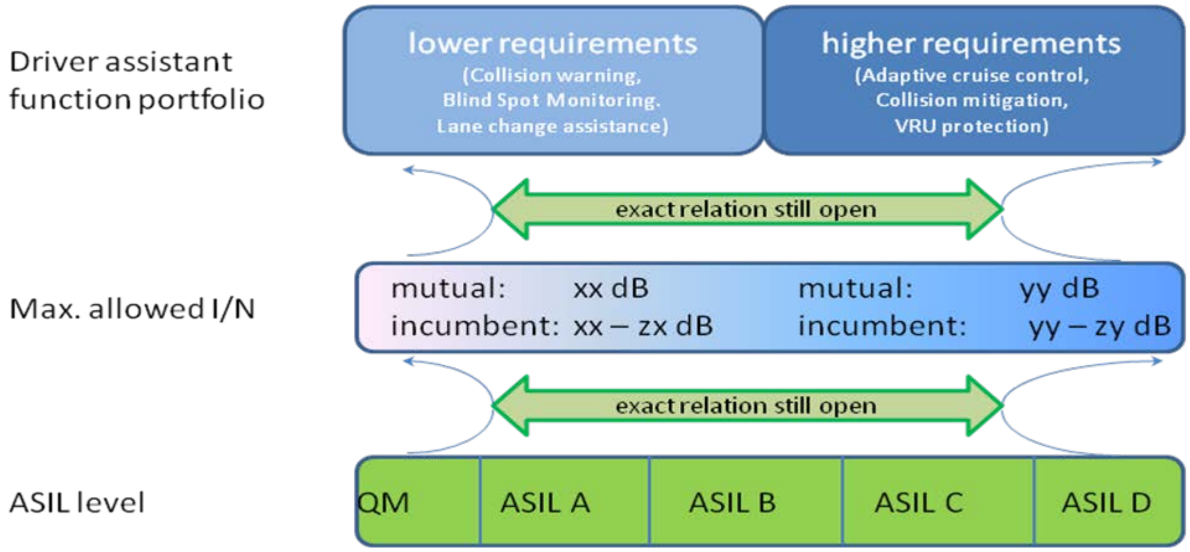


**Figure 1: Requirements mapping of ASIL and mitigation margin to different assistant functions**

There are two different I/N classes defined that represent an apportionment between mutual (i.e. all the other automotive radars) and incumbent (i.e. all possible other interferers) frequency users. To limit the impact from incumbent users their I/N value is typically between 10 and 20 dB lower (c.f. apportionment).
For applications with higher safety requirements the absolute I/N values are smaller compared to those with lower safety requirements.

Now, after having found the maximum possible I/N in relevant scenarios, the required mitigation margin can be determined (see example in Figure 2).

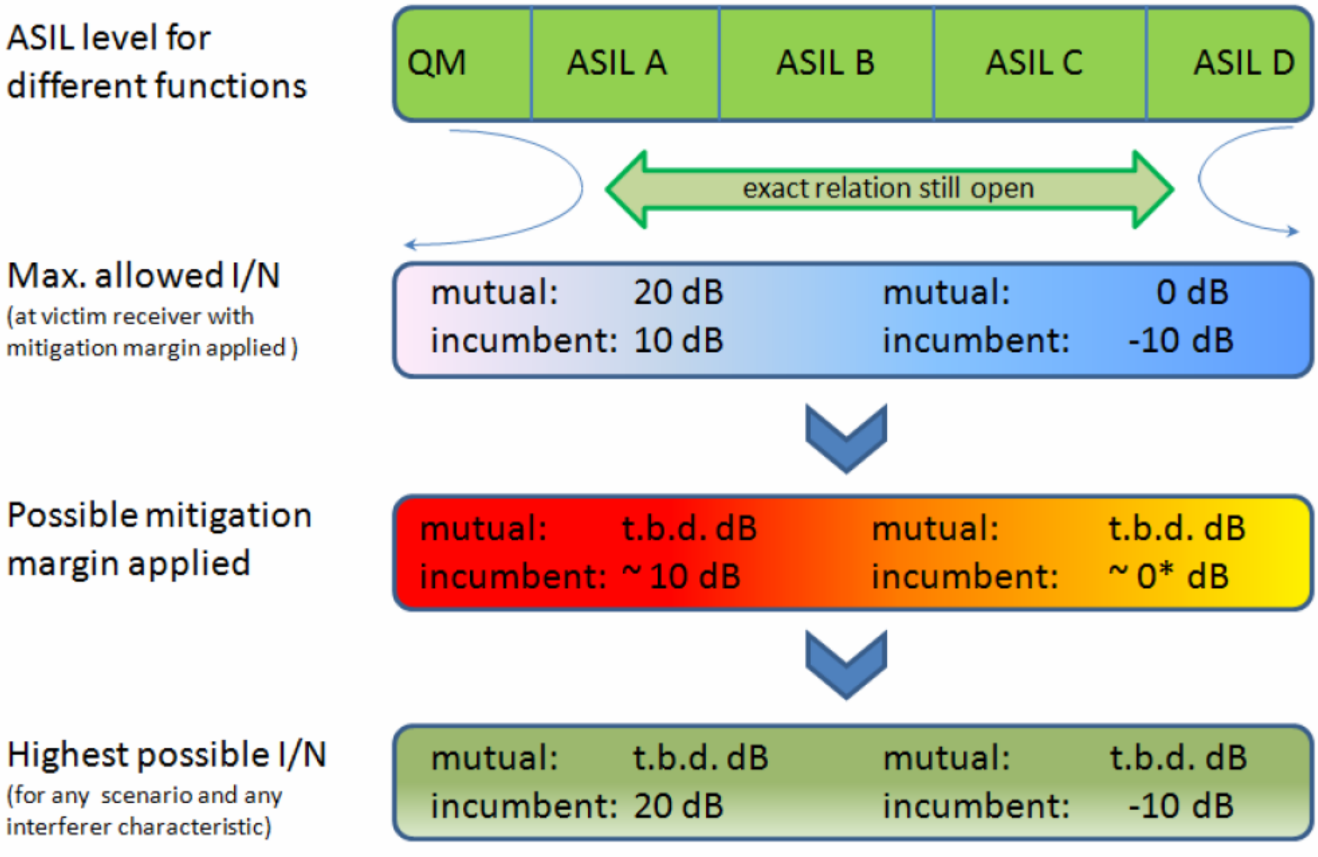


**Figure 2: Exemplary requirements mapping of ASIL, I/N and mitigation margin.**

For the mitigation techniques and their respective mitigation margins the situation is as follows:

a) For functions with lower requirements the robustness of the technique is less binding

b) The given mitigation margin for applications with higher safety requirement has to be guaranteed under any circumstance in order not to jeopardize the proper radar functionality. This is especially important during critical situations where a sudden system out-of-order (due to high interference power received in that moment) is not acceptable at all.

In Table 3 of Deliverable 5.1 the nine most promising interference mitigation techniques are listed and the estimated or tested mitigation margins (ranging from a few dB up to infinite dB) are provided. The validation of the effectiveness of the mitigation techniques and the provided mitigation margin values were confirmed either by simulation or during the practical test campaigns. Further reading and results can be found in the Deliverables [D2.7] and [D3.6].

Basically all mitigation techniques can be combined or even concatenated with each other and the respective mitigation margins of each technique can be added up to result in an overall mitigation margin. In very specific constellations special care or precautions have to be taken or respected (see Table 2). It would be detrimental if the usage of two mitigation techniques would influence each other and probably reduce the overall mitigation margin below the value of each of the individual technique in the worst case. Any critical constellation will be mentioned in chapter 4 in the relevant paragraphs.

| | | | combinable | concatenable | exceptions or remarks |
|---|---|---|---|---|---|
| MITIGATION TECHNIQUES | T3.1 | CFAR (constant false alarm rate) for interference mitigation | yes | yes | needs frequency domain processing |
| | T6.5 | Detect interference and change transmit frequency range of chirps | yes | yes | needs enough available bandwidth |
| | T2.1 | Using pauses of random length between chirps or pulses | yes | yes | limited mitigation margin |
| | T3.4 | Application of driving direction specific pre-defined frequency band separation | yes | yes | needs global coordination work |
| | T6.2 | Detect interference and repair Rx results (Time domain) | yes | yes | - |
| | T2.2 | Using random sequence of chirp types (Up-chirp, Down-chirp, CW-Chirp) | yes | yes | - |
| | T5.4 | Digital Beam Forming | yes | yes | - |
| | T6.4 | Detect interference and change timing of transmit chirp or pulses | yes | yes | similar to T2.1 |
| | T1.2 | Specific polarisation following the Radar location (frontal, rear, side) | yes | yes | similar to T3.4 |

**Table 2: Overview of different mitigation techniques w.r.t. combination or concatenation capability**

In the following chapter 4, guidelines for the 9 mitigation techniques as mentioned in Table 2 are provided in tabular form.

# 4. Guidelines and implementation hints for the best-ranked set of mitigation techniques

In the following nine sub-chapters the essential hints and guidelines for the most important mitigation techniques studied within the MOSARIM project are listed.

After a short description of the functional principle the following topics are addressed:

1) **Modulation scheme dependent application hints**
   In this section guidelines are given that are specific when using the different modulation schemes. For example some modulation schemes may be dithered in the time or/and frequency domain to reduce coincidence of identical transmitted waveforms when several radar devices are operated at the same time and in the same location.

2) **Hints and precautions for implementation**
   A short explanation regarding implementation of the technique is given. This refers to:
   a) Implementation on Rx or Tx side
   b) Implementation via software and probably significant additional effort regarding processing time or hardware
   c) Implementation by hardware which results in the use of additional or special hardware components

3) **Measures to avoid interaction with other mitigation techniques**
   If a known precaution has to be taken when using two or more mitigation techniques at the same time it will be stated here. For example the mitigation method T6.5 – "Detect interference and change frequency range of chirps" and T3.4 – "Application of driving direction dependent pre-defined frequency band separation" may interact when the radar sensors jump in an already occupied pre-defined sub-band by error or by missing coordination.

4) **Coordination and standardization activities**
   Depending on the interference mitigation technique applied, it may be necessary to define frequency harmonization aspects. For example, if the respective technique involves specific sub-band frequency partitioning this has to be specified and made mandatory in the relevant standards (e.g. ETSI automotive standard EN 301 091), in order to assure the effectiveness by making it generally binding for all existing radar systems.

5) **Final remarks and hints**
   In this table box any further remark or hint that is relevant for the respective guideline may be mentioned.

## 4.1 CFAR mitigation technique guidelines

| Description of the functional principle |
|---|
| The detection threshold in the frequency domain analysis (typically a FFT analysis) is adaptively changed to keep detection probability and false alarm rate to a preselected value. In case of a noise-floor increase by an interfering signals the peak detection threshold in the spectral evaluation is increased accordingly. As a negative side-effect the radar sensitivity is reduced because the SNR is decreased by the threshold level adaption. |
| **Modulation schemes dependent application hints** |
| No limitation to any frequency modulation scheme. Not applicable for UWB or pulsed radar systems that work in the time domain. |
| **Hints and precautions for implementation** |
| No hardware modifications required. The variable threshold adaptation should be limited to a given range and stay in any case significantly below the dynamic range of the input stage (i.e. when a 10 bit ADC converter is used with a dynamic range of 60 dB the CFAR range should be maximum 20 dB). |
| **Measures to avoid interaction with other mitigation techniques** |
| Nothing known for the time being. |
| **Coordination and standardization activities** |
| No coordination or standardization activity needed. |
| **Final remarks and hints** |
| Standard technology that is implemented in almost all existing automotive radars using threshold detection and evaluation in the frequency domain.<br>Because the CFAR algorithm reduces the overall radar sensitivity, the amount of threshold change should be forwarded to later processing stages to be aware of the sensitivity decrease.<br>CFAR used as standalone mitigation technique is not sufficient to guarantee interference free operation for functions with higher requirements. |
| **Mitigation margin and site of operation** |
| Mitigation margin of this technique: ca. 10 – 20 dB<br>Mitigation is operational on: Rx side |

## 4.2 Detect interference and change transmit frequency range of chirps guidelines

| Description of the functional principle |
|---|
| Interference is detected in the radar received signal by adequate measures and techniques. The radar system then changes the occupied frequency band into an area where no interference from other devices is detected. The method can be extended from simple sub-band changing by defining specific sensor operation states for carrier frequency, modulation type of transmit wave, orientation of polarization, transmission cycle and modulation code. When more than one radar system is mounted on the same vehicle the state of each sensor can be communicated over the network connection to avoid interference among radar sensors mounted on the same vehicle. The modulation state of a sensor can further be broadcasted to sensors on other vehicles to make this method even more efficient. |
| **Modulation schemes dependent application hints** |
| Limited to FMCW and FSK modulation scheme. Not applicable for UWB or pulsed radar systems. |
| **Hints and precautions for implementation** |
| The needed operational bandwidth for a given application should not be sacrificed to be able to use this mitigation technique. Due to the totally available bandwidth of 1 and 4 GHz respectively, the 77 GHz and 79 GHz bands are best suited for this mitigation technique. |
| **Measures to avoid interaction with other mitigation techniques** |
| Special algorithms on how to select the other sub-bands are needed to avoid that all radars are continuously trying to hop in free sub-bands that are shortly later occupied by other radars. |
| **Coordination and standardization activities** |
| Activities to define globally available sub-bands in the automotive frequency bands at 24 GHz, 77 GHz and 79 GHz are needed. Further coordination with pre-selected, driving-direction dependent frequency bands may be necessary. |
| **Final remarks and hints** |
| This method can fully suppress disturbance in case of using a sub-band where interference signal is not present.<br>This mitigation technique guarantees interference free operation for functions with higher requirements in case of non-overlapping sub-bands even when applied in standalone mode. |
| **Mitigation margin and site of operation** |
| Mitigation margin of this technique: up to infinity dB<br>Mitigation is operational on: Tx side |

## 4.3 Using pauses of random length between chirps or pulses guidelines

| Description of the functional principle |
|---|
| If coherent interference occurs over many chirp or pulse cycles, time adaptive filtering in the signal processing chain might adjust to it and sensor performance deteriorates for the end-user. By introducing a continuously changing pause of random length between the chirps or pulses, the danger of identical repetitive interference can be reduced. This method is commonly named dithering and can be applied in time and/or frequency domain. |
| **Modulation schemes dependent application hints** |
| Can be applied to any kind of modulation scheme. |
| **Hints and precautions for implementation** |
| The dithering in time and frequency domain has to be done with well-selected codes to generate both an equally distributed and totally random jitter sequence that further on changes its pattern over the time. |
| **Measures to avoid interaction with other mitigation techniques** |
| Nothing known for the time being |
| **Coordination and standardization activities** |
| No coordination or standardization activity needed. |
| **Final remarks and hints** |
| It has to be checked in detail whether the simple idea of using random pauses is patent protected.<br>Use of that idea in a more complex context seems to be protected<br>This mitigation technique used as standalone is not sufficient to guarantee interference free operation for functions with higher requirements |
| **Mitigation margin and site of operation** |
| Mitigation margin of this technique: only a few dB<br>Mitigation is operational on: Tx side |

## 4.4 Application of driving direction specific pre-defined frequency band separation guidelines

| Description of the functional principle |
|---|
| A very efficient and simple implementation of interference mitigation with full interference suppression capability is possible by predefined frequency band separation. This can be either done on an application level (e.g. the 77 GHz ACC band for LRR and the 24GHz band for MRR and SRR applications respectively) or for a given frequency range by pre-defined frequency sub-bands for the different radar beam emission directions with respect to the vehicle axis (e.g. using a 77 GHz to 79 GHz sub-band for all MRR and SRR radars that are looking in the vehicle driving direction and a 79-81 GHz sub-band for MRR and SRR looking in reverse driving direction). |
| **Modulation schemes dependent application hints** |
| Can be applied to any kind of modulation scheme. |
| **Hints and precautions for implementation** |
| For a flexible, multi-functional concept the HW shall be capable to operate in all available sub-bands; for simple solutions operation in the relevant sub-band may be sufficient.<br>*Critical parameter*: the broadband capability of the radar device if multi-usage in all sub-bands is foreseen |
| **Measures to avoid interaction with other mitigation techniques** |
| Nothing known for the time being. |
| **Coordination and standardization activities** |
| Yes, the pre-defined sub-bands definition w.r.t. the vehicle driving direction should be harmonized. |
| **Final remarks and hints** |
| This mitigation technique used as standalone is not sufficient to guarantee interference free operation for functions with higher requirements for traffic situations with oncoming vehicles. For this situation a combination with the technique as described in 4.2 could solve this shortcoming. |
| **Mitigation margin and site of operation** |
| Mitigation margin of this technique: up to infinity dB for same driving direction<br>Mitigation is operational on: Tx side |

## 4.5 Detect interference and repair Rx results (Time domain) guidelines

| Description of the functional principle |
|---|
| Interference is detected in a time signal using statistical properties of the received signal. The method is based on the assumption that interfered signal includes also higher frequency components. The interference can be detected with statistical signal parameters like variance or estimation of slope (first derivative) and comparison with a defined threshold. If the parameter exceeds a certain threshold the samples are marked as being interfered. Samples marked as interfered are substituted by either zeros, interpolated or extrapolated samples (so-called signal healing). |
| **Modulation schemes dependent application hints** |
| Can be applied to any kind of modulation scheme. |
| **Hints and precautions for implementation** |
| The implementation will be done via software on Rx side. For this technique more processing power is necessary. In some cases also a faster ADC is needed. |
| **Measures to avoid interaction with other mitigation techniques** |
| Nothing known for the time being. |
| **Coordination and standardization activities** |
| No coordination or standardization activity needed. |
| **Final remarks and hints** |
| There are already some patents for some of the algorithms that may prevent global proliferation. This mitigation technique used as standalone is not sufficient to guarantee interference free operation for functions with higher requirements |
| **Mitigation margin and site of operation** |
| Mitigation margin of this technique: ca. 20 dB possible<br>Mitigation is operational on: Rx side |

## 4.6 Using random sequence of chirp types guidelines

| Description of the functional principle |
|---|
| If a constant time-sequence is used, interference could generate a constant pattern of disturbance over many chirps and the time-adaptive filtering in the signal processing chain might adjust to it. Thus sensor performance becomes worse for the end-user.<br>By introducing a random time-sequence of chirps, the danger of a constant pattern of disturbance can be reduced. |
| **Modulation schemes dependent application hints** |
| For FMCW, FSK+FMCW modulation schemes. |
| **Hints and precautions for implementation** |
| This technique is a software implementation on Tx side. A modification of the hardware is not required. Consequences for getting enough radar information on Rx-side may be an open question. |
| **Measures to avoid interaction with other mitigation techniques** |
| Nothing known for the time being. |
| **Coordination and standardization activities** |
| No coordination or standardization activity needed. |
| **Final remarks and hints** |
| It has to be checked in detail whether the simple idea of using random time-sequence of chirps is patent protected. Use of that idea in a more complex context seems to be protected<br>This mitigation technique used as standalone is not sufficient to guarantee interference free operation for functions with higher requirements |
| **Mitigation margin and site of operation** |
| Mitigation margin of this technique: only a few dB<br>Mitigation is operational on: Tx side |

## 4.7 Digital Beam Forming guidelines

| Description of the functional principle |
|---|
| Identify the incident angle of interference and adaptively place a notch in this direction to suppress the interfering signal. This is done by changing the beam forming weighting of the individual, spatially separated receive channels. |
| **Modulation schemes dependent application hints** |
| Can be applied to any kind of modulation scheme. |
| **Hints and precautions for implementation** |
| The mitigation performance strongly depends on the number of digital antenna beams used. The higher the number of digital beams is the better the mitigation margin will be. |
| **Measures to avoid interaction with other mitigation techniques** |
| Nothing known for the time being. |
| **Coordination and standardization activities** |
| If a high number of digital beams is used the regulated maximum EIRP density may become a limiting factor (due to very high dBi antenna gain). |
| **Final remarks and hints** |
| To avoid excessive cost increase the number of necessary digital beams should be specified by the application and not by the wanted mitigation margin.<br>This mitigation technique used as standalone is not sufficient to guarantee interference free operation for functions with higher requirements |
| **Mitigation margin and site of operation** |
| Mitigation margin of this technique: only a few dB<br>Mitigation is operational on: Tx side |

## 4.8 Detect interference and change timing of transmit chirp or pulses guidelines

| Description of the functional principle |
|---|
| Interference can be limited or avoided by accurately chosen timing for transmitted signals. If interference occurs, the time delay between two following chirps, pulses or a sequence of defined chirps or pulses is changed to avoid signal overlapping in the time domain. |
| **Modulation schemes dependent application hints** |
| Can be applied to any kind of modulation scheme. |
| **Hints and precautions for implementation** |
| The maximum mitigation margin that can be achieved depends on the ratio between Tx_on and Tx_off time. If the ratio is very low the mitigation is rather high and vice versa. In any case enough observation time is needed given by the required application dynamics. |
| **Measures to avoid interaction with other mitigation techniques** |
| Nothing known for the time being. |
| **Coordination and standardization activities** |
| Too short Tx_on or Tx_off times may result in an UWB like operation that has to be at least cross checked with existing regulations regarding conformity. |
| **Final remarks and hints** |
| The effect depends strongly on type and modulation of the interferer. For two FMCW radars with the same modulation (slope and timing) the method significantly reduces interference. For two FMCW radars with various modulations (significant difference in chirp slopes) only a minor mitigation effect is expected.<br>This mitigation technique used as standalone is not sufficient to guarantee interference free operation for functions with higher requirements |
| **Mitigation margin and site of operation** |
| Mitigation margin of this technique: a large number of dBs is expected<br>Mitigation is operational on: Tx side |

## 4.9 Specific polarization following the Radar location guidelines

| Description of the functional principle |
|---|
| MOSARIM Task 4.1 "Ground truth interference assessment" has shown, that different polarization of the emitted radar waves can significantly reduce interference effects. One proposal for a possible polarization configuration:<br>Forward applications : horizontal polarization for 77 GHz Radar & vertical for 24 GHz Radar<br>Rear applications : Vertical polarization for 77 GHz Radar & horizontal for 24 GHz Radar<br><br>Alternative proposal of another possible polarization configuration:<br>Forward applications : horizontal polarization for 77 GHz Radar & horizontal for 24 GHz Radar<br>Rear applications : Vertical polarization for 77 GHz Radar & vertical for 24 GHz Radar<br><br>There are many other proposals possible |
| **Modulation schemes dependent application hints** |
| Can be applied to any kind of modulation scheme. |
| **Hints and precautions for implementation** |
| The radars already on the market use either horizontal, vertical or slant polarization because no specific polarization is needed for a given application. The used polarization directions are more or less equally distributed among the existing sensors.<br>Environmental effects on polarization are negligible and therefore do not influence the selection of the applied polarization plane. |
| **Measures to avoid interaction with other mitigation techniques** |
| Nothing known for the time being. |
| **Coordination and standardization activities** |
| Agreement regarding the assignment of specific polarization for e.g. forward or backward applications is needed. |
| **Final remarks and hints** |
| A pre arrangement of specific polarization has to be done before products are brought on the market. For all the existing products it is not possible to coordinate the polarization planes a posterior. This mitigation technique used as standalone is not sufficient to guarantee interference free operation for functions with higher requirements |
| **Mitigation margin and site of operation** |
| Mitigation margin of this technique: ca. 15 dB (for linear co-to cross-polarization)<br>Mitigation is operational on: Tx side |

# 5. Validation checks with the simulation tool-chain

Some of the described mitigation techniques were verified in a simulation tool-chain developed by the project partner Karlsruhe Institute of Technology (KIT). Simulation was either conducted due to the complexity of the implementation in a real target system, by studying the effects with small incremental changes or with Monte-Carlo methods.
More or less qualitative results for some of the mitigation techniques can be found in the following sections. A detailed description regarding the parameter setup for simulation can be found in [D3.6].

## 5.1 Constant False Alarm Rate threshold

In figure 3 the operation principle of the CFAR algorithm is shown by doing a simulation run with a disturbed and an undisturbed identical radar signal.

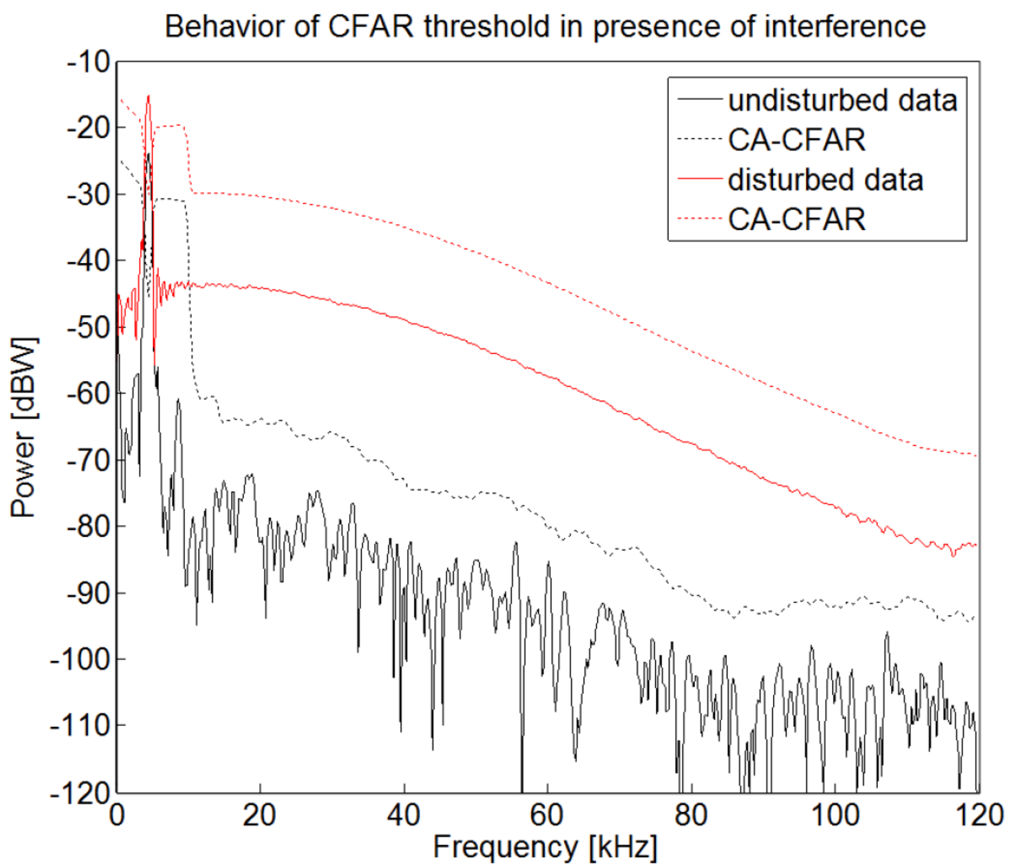


**Figure 3: Operation principle of the CFAR algorithm**

## 5.2 Interference mitigation by variable pause times

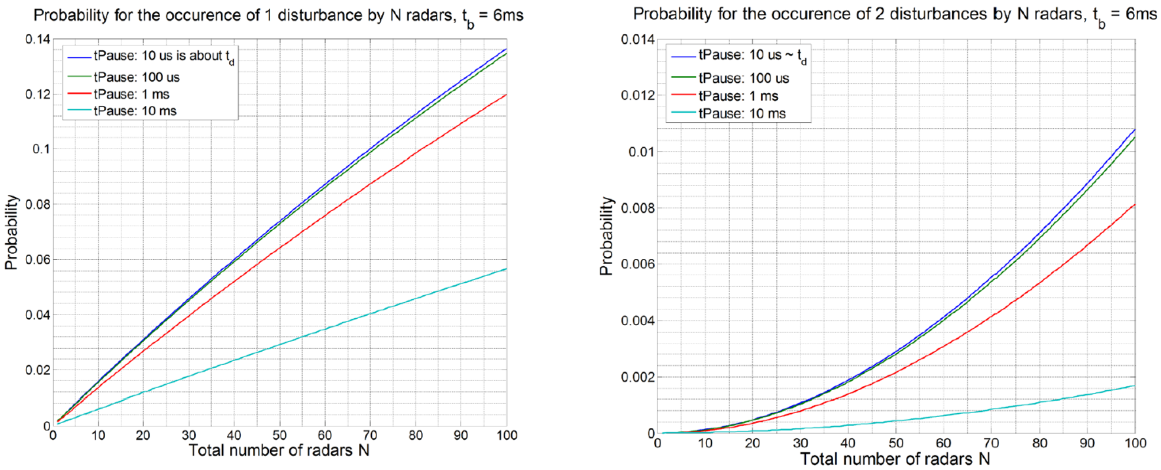


**Figure 4: Simulated interference mitigation effects by variable pause times**

In figure 4 the effect of a variable pause time is simulated for probability occurrence of one or two disturbances by N radar systems. The longer the pause time is chosen, the lower the interference probability will be.

## 5.3 Detect interference and repair time domain received data

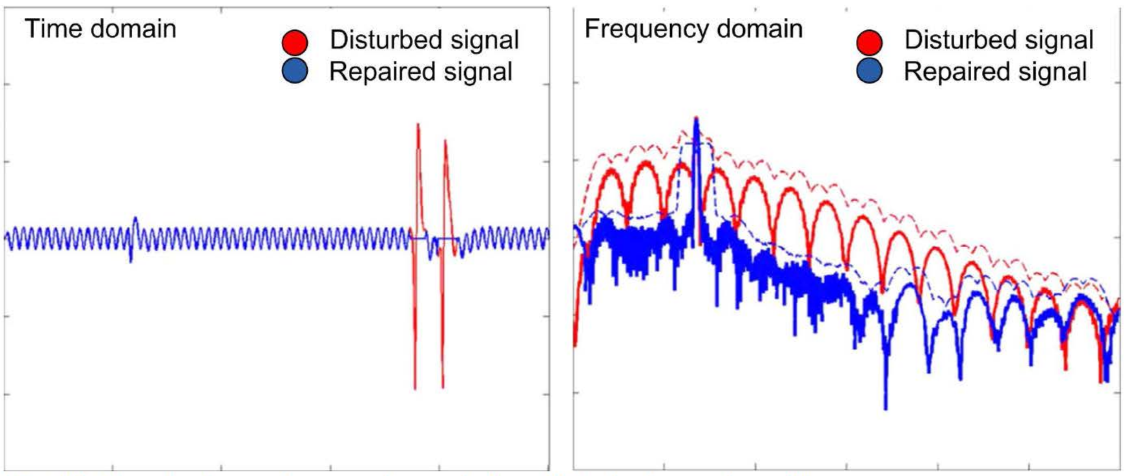


**Figure 5: Simulated interference mitigation effects by variable pause times**

In figure 5 the detect interference and repair in the time domain is sketched. A synthetic radar signal is interfered twice with a rather high spike signal, resulting in a noise level increase of ca. 20 dB. By healing the signal in the time domain, the noise floor increase can be almost completely counter-acted.

# 6. Checklist for interference troubleshooting

In the DoW version 1.8a in task 5.2 it is mentioned to establish a set of guidelines and a checklist that can be used in the case that harmful interference happens or is suspected to be the origin of a system malfunction on the road.
While guidelines were derived in chapter 4 for the different mitigation techniques, the generation of a global checklist turned out to be more complicated.
To investigate and troubleshoot potential interference risks and trying to identify the possible root cause of the radar sensor malfunction is a rather time-consuming task and typically requires a so-called FMEA. Conducting a process or system FMEA would go far beyond the scope of this task.

Describing processing steps how to isolate and find root causes for unexpected or sudden system malfunction that may root back to the applied mitigation techniques requires even more. To determine whether performance degradation is present or not requires beforehand that a standard performance reference index is defined. Then, by continuously monitoring the system performance index, possible performance degradation can be detected.

A general checklist or cooking-book to investigate for interference-related system malfunctions is not realizable. However, as a general recommendation it can be stated that when applying the mitigation techniques correctly and respecting the hints of the guidelines in chapter 4 the risk of mutual interference between automotive radars can be kept to a minimum or even negligible level.

# 7. Conclusions

Interference-free operation of automotive radars is a pre-condition for safety-critical applications and even for warning or comfort function with lower safety requirements mitigation techniques should be applied to assure sufficient system availability (or quality of service). The mitigation techniques dealt with in this document operate on different levels (transmit or receive side), with different performance (only a small mitigation margin up to complete interference suppression) and by different implementation forms and techniques.

Some of them need frequency coordination or standardization activities while others can work stand-alone without any influence to other countermeasures or the entire radar environment.

The knowledge of the whole MOSARIM consortium is expressed in the guidelines elaborated in chapter 4. This first assessment on how to implement the mentioned mitigation techniques in the right way will serve as a starting platform to progress towards recommendations and harmonized standards on how to operate automotive radars in the best interference-free way. As soon as such a description will be available in the next step the definition and validation of appropriate testing procedures for radar equipment proofing and labelling can be approached.

In the upcoming last Deliverable [D5.4] of work package WP5 ideas and a more detailed outlook will be given.

# Bibliography

[DoW] Description of work MOSARIM project V1.8a, 19.09.2012

[D1.4] Deliverable to MOSARIM Task 1.4 “Impact study of the interference effects with respect to ASIL”, 20.12.2011

[D1.5] Deliverable to MOSARIM Task 1.4 “Short report on state-of-the-art interference mitigation techniques”, 28.06.2010

[D2.7] Draft Deliverable to MOSARIM Task 2.7 “Validation check of simulation models with selected real world laboratory tests”, 30.11.2012

[D3.6] Deliverable to MOSARIM Task 3.6 “Optimisation of mitigation techniques (iterative approach)”, 21.09.2012

[D5.1] Deliverable to MOSARIM Task 5.1 “Classification of the different interference countermeasures regarding their effectiveness and applicability to different safety”, 01.10.2012

[D5.2] Deliverable to MOSARIM Task 5.2 “Guidelines to reduce mutual interference effects and to cope with interference cases”, 30.11.2012

[D5.3] Deliverable to MOSARIM Task 5.3 “Recommendations on sensor design, mounting and operational parameters to minimize radar interference”, 30.11.2012

[D5.4] Deliverable to MOSARIM Task 5.4 “Conclusion and outlook how to solve still open challenges”, xx.12.2012

# Abbreviations

| | |
|---|---|
| ACC | Adaptive Cruise Control |
| ASIL | Automotive Safety Integrity Level |
| BSD | Blind Spot Detection |
| CFAR | Constant False Alarm Rate |
| CW | Continuous Wave |
| DoW | Description of Work |
| E/E | electrical and electronic |
| EMC | Electromagnetic Compatibility |
| FCW | Forward Collision Warning |
| FIT | Failure in Time |
| FLR | Forward Looking Radar |
| FMCW | Frequency Modulated Continuous Wave |
| FMEA | Failure Mode and Effects Analysis |
| FSK | Frequency Shift Keying |
| I/N | Interference power over noise power ratio |
| ISO | International Standardization Organization |
| MRR | Medium Range Radar |
| LCA | Lane Change Assist |
| LRR | Long Range Radar |
| QM | Quality management |
| SRR | Short Range Radar |
| UWB | Ultra Wide Band |