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MOre Safety for All by Radar Interference Mitigation

D5.1–Classification of the different interference countermeasures regarding their effectiveness and applicability to different safety functions

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SEVENTH FRAMEWORK PROGRAMME

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Revision chart and history log

Version	Date	Reason
0.1	15.07.2012	Initial version by S. Germaine
0.2 to 0.9	multiple	Several intermediate versions
1.0	13.09.2012	Version for peer review
1.1	18.09.2012	Comments and revisions from A. John
1.2	24.09.2012	Rework and add of safety/comfort definitions from S. Germaine
1.3	25.09.2012	Further modifications following discussions during Plenary in Paris
1.4	01.10.2012	Final version for submission
1.5	14.12.2012	Table 5 updated – as requested from reviewers in the annual project review on 12.12.2012 in Brussels

Applicable documents

Ref.	Date	Title
MOSARIM D3.1-V1.0	24.08.2012	Use cases description list for simulation scenarios
MOSARIM D3.2-V1.3	28.10.2011	Investigation and evaluation of interference mitigation techniques
MOSARIM D3.6-V1.0	24.08.2012	Optimisation of mitigation Techniques

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Executive summary

The objective of Task 5.1 is to assess the effectiveness of the different countermeasures for mutual vehicular radar interferences, using the results from working package 3 (Elaboration of efficient interference countermeasures on simulation basis) and working package 4 (Validation of simulated interference countermeasures with selected use cases).

WP 3, in particular in Deliverable D3.6, gives detailed analyses of each of the selected countermeasures and assesses their effectiveness.

In WP 4, many test campaigns have been performed to see and assess the real effects of countermeasures applied on the prevailing interference signals.

This deliverable tries to summarize this information in order to conclude on the efficiency of the countermeasures (in term of interference mitigation margin).

A matrix that shows compatibility between countermeasures and applications was build in order to evaluate the applicability of the countermeasures.

Finally, in the conclusion possible ways to derive guidelines in the next tasks of WP5 are given.

1 Introduction

In work packages 3 and 4 several interference countermeasures have been considered, implemented and tested in various worst-case scenarios.

Work package 3 provided test results from simple and complex simulations whereas work package 4 concentrated on real measurements conducted on test tracks and closed roads.

Task 5.1 will classify these countermeasures with respect to their effectiveness and applicability to different levels of safety functions envisioned for future vehicles. This work will be useful for others tasks within WP5 in order to derive guidelines or recommendations.

Section 2 of this document presents the different mitigation techniques and provides a classification of the countermeasures with regard to 3 parameters. It also summarized results of simulations and real tests measurements regarding the efficiency of the selected countermeasures.

Section 3 shows the possible applications of a radar sensor assessed in WP3 and classifies between applications with lower or with higher safety requirements.

In Section 4, an overview of the applicability of the different countermeasures with regard to the automotive radar sensor applications is shown.

Finally, section 5 gives a conclusion and perspective that can be used in the next WP5 tasks.

2 Considered mitigation techniques

The deliverable D3.2 listed and ranked different mitigation techniques on a theoretical point of view, independent from individual requirements of the different radar applications. Among the different mitigation techniques, nine were found of particular interest for implementation in automotive radars.

2.1 Theoretical, heuristic and estimation-based considerations

The following Table 1 recapitulates the main ranking results and findings of deliverable D3.2.

Table 2 now classifies the countermeasures mentioned in Table 1 according to Tx side, Rx side and frequency regulation categories.

Ref.	Title	Total ranking from D3.2	Selection Status
T3.1	CFAR (constant false alarm rate) for interference mitigation	470	**Selected techniques for MOSARIM**
T6.5	Detect interference and change transmit frequency range of chirps	463	
T2.1	Using pauses of random length between chirps or pulses	460	
T3.4	Application of driving direction specific pre-defined frequency band separation	437	
T6.2	Detect interference and repair Rx results (Time domain)	433	
T2.2	Using random sequence of chirp types (Up-chirp, Down-chirp, CW-Chirp)	432	
T5.4	Digital Beam Forming	425	
T6.4	Detect interference and change timing of transmit chirp or pulses	423	
T1.2	Specific polarization following the Radar location (frontal, rear, side)	421	
T6.3	Detect interference and repair Rx results (Frequency domain)	408	**Non selected techniques for MOSARIM**
T6.1	Detect interference and omit Rx results	395	
T3.3	Interference detection by summing higher part of FFT spectrum [only detection, no mitigation]	383	
T5.3	EIRP limitation	382	
T1.1	Using 45° polarization	373	
T3.2	Multi-slope FMCW radar	361	
T6.8	Communicate and avoid	359	
T4.1	FH-SS (Frequency Hopping Spread Spectrum) coding modulation	354	
T5.2	Extended Space-Time domain Adaptive Processing (STAP)	350	
T6.7	Listen before talk	344	
T6.6	Detect interference and change beam scanning	305	
T4.2	DS-CDMA (Direct Sequence - Coding Division Multiple Access) coding modulation	298	
T5.1	Scanned antenna beam (one continuous scan per cycle)	245	

Table 1: List of mitigation techniques as compiled based on mostly theoretical considerations in deliverable D3.2.

When thinking about future work regarding possible guidelines derivation, it is of interest to class the different countermeasures according to (see also Table 2):

- techniques at Tx side
- techniques at Rx side
- techniques requiring regulatory harmonization

Mitigation techniques at Tx side		Mitigation techniques at Rx side		Mitigation techniques requiring regulatory harmonization	
T6.5	Detect interference and change transmit frequency range of chirps	T3.1	CFAR (constant false alarm rate) for interference mitigation	T3.4	Application of driving direction specific pre-defined frequency band separation
T2.1	Using pauses of random length between chirps or pulses	T6.2	Detect interference and repair Rx results (Time domain)	T1.2	Specific polarization following the radar location (frontal, rear, side)
T2.2	Using random sequence of chirp types (Up-chirp, Down-chirp, CW-Chirp)	T5.4	Digital Beam Forming	T5.3	EIRP limitation
T6.4	Detect interference and change timing of transmit chirp or pulses	T6.3	Detect interference and repair Rx results (Frequency domain)	T1.1	Using 45° polarization
T3.2	Multi-slope FMCW radar	T6.1	Detect interference and omit Rx results	T6.8	Communicate and avoid
T4.1	FH-SS (Frequency Hopping Spread Spectrum) coding modulation	T3.3	Interference detection by summing higher part of FFT spectrum [only detection, no mitigation]	T6.7	Listen before talk
T6.6	Detect interference and change beam scanning	T5.2	Extended Space-Time domain Adaptive Processing (STAP)		
T4.2	DS-CDMA (Direct Sequence - Coding Division Multiple Access) coding modulation				
T5.1	Scanned antenna beam (one continuous scan per cycle)				

Table 2: Countermeasures classified according to Tx side, Rx side and frequency regulation

In further tasks of WP3, some interference mitigation techniques were assessed in simulations. Six of them have been tested and analyzed during the MOSARIM closed road tests (see work package 4 for further details and results).

2.2 Simulation

The deliverable D3.6 "*OPTIMISATION OF MITIGATION TECHNIQUES*" presents results from simulative and analytical investigations.

Simulations were done for both correlated and uncorrelated interference signals.

For uncorrelated interference, it is interesting to note that all the above mentioned mitigation techniques have the ability to work well and mitigate the interference impact with a very high margin. In particular, the CFAR method (T3.1) is already implemented in all the sensors used within the MOSARIM framework and "provide a decent performance versus a noise floor increase".

For correlated signals (usually due to identical signal modulation or waveform in time, frequency and phase), "*these mitigation methods reduce the probability of interference significantly, especially when several periods are observed (so-called tracking and coasting)*".

Analyses show that also many combinations of different mitigation techniques are feasible, thereby summing up the individual interference mitigation margin of each countermeasure.

2.3 Real world road tests

Real world road test results of the measurement campaigns conducted on the different sites (test track, tunnel and car park) will be summarized in the up-coming deliverable D4.5.

Tests were performed inside laboratory test chambers, on test tracks, in a tunnel and in a closed car park presenting many metallic T-beams (the last one was not yet performed at the time of submission of this document).

As mentioned before, all available radar sensors implemented the CFAR method. Many of the different tested sensors also implemented at least one of the other mitigation techniques.

Results show that the interference was not as large as expected at project start:

- The typical noise floor increase is below 10dB in most scenarios. Some rare cases show an increase of more than 10dB, usually because of static worst cases or long-term interference scenarios (e.g. a car equipped with a front sensor following a car equipped with a rear sensor). However this increase barely leads to a loss of an already tracked target.
- No ghost targets were observed during all the tests. This is mainly due to the tracking software in the post-processing stage that will suppress a potential arising ghost target in the rare cases this might could happen.

2.4 Summarized efficiency

The following Table 3 summarizes the typical interference mitigation margin (either from tests or estimated) and some comments for each countermeasure.

Countermeasures		Interference mitigation margin in dB (measured or estimated)	Comment
T3.1	CFAR (constant false alarm rate) for interference mitigation	ca. 10 - 20 dB	It can be used for all kind of functions without any constraints CFAR performance slightly influence

Countermeasures		Interference mitigation margin in dB (measured or estimated)	Comment
			by number of targets
T6.5	Detect interference and change transmit frequency range of chirps	up to infinity dB	Infinite mitigation margin can be obtained for 2 radars, but will be reduced if many interferers are present and band overlapping occurs. Efficiency depends on the occupied bandwidth and the bandwidth available
T2.1	Using pauses of random length between chirps or pulses	only a few dB	suppression of ghost targets and results in increase of noise floor. Typically measurement to pause ratio is maximum 50% => on average 3 dB mitigation margin
T3.4	Application of driving direction specific pre-defined frequency band separation	up to infinity dB for same driving direction, but no mitigation margin for crossing traffic	This needs worldwide coordination to become effective. For crossing traffic a special measure has to be found.
T6.2	Detect interference and repair Rx results (Time domain)	up to ca. 20 dB possible	The influence of fast or slow crossing FM chirps still needs further investigation on mitigation margin impact
T2.2	Using random sequence of chirp types (Up-chirp, Down-chirp, CW-Chirp)	Only a few dB	Suppression of ghost targets and results in increase of noise floor. Only limited mitigation margin capability if done in the same frequency range
T5.4	Digital Beam Forming	Only a few dB	Mitigation effect depends on beamwidth (space domain)
T6.4	Detect interference and change timing of transmit chirp or pulses	a large number of dBs is expected	With good timing and arrangement of FM ramps high margin can be reached. A prerequisite is that all radars use same ramp duration to make synchronisation without ramp crossing possible
T1.2	Specific polarisation following the Radar location (frontal, rear, side)	typically ca. 15 dB for co- to cross-polarization (linear)	This is already partially used for ACC radars that have 45 degree slant polarization (reduced interference from oncoming radars by 15 dB)

Table 3: Interference mitigation margin

Note for cells marked in grey: Not tested within MOSARIM / margin is only estimated

Results show that interference can be mitigated from a few dBs to a theoretical infinite number of dBs (i.e. no more interference at all). Some of these countermeasures can be easily implemented by radar manufacturers and will increase the sensor robustness. Others will need upstream the development of commonly agreed international regulations, such as for example frequency planning and allocation, and therefore may need more time to become of interest.

In the following chapters the applicability of countermeasures for the different radar functions is evaluated.

3 List of considered radar functions

Driver assistance functions that use automotive radars were already listed in detailed in deliverable D3.1. The following Table 4 shows all these functions.

Each function can have safety impact and residual risk for the driver. Automotive Safety Integrity Level (ASIL) levels are defined from A to D. To estimate the ASIL level for a function, three criteria are evaluated:

- The **severity** of potential harm, from no injuries (S0) to fatal injuries (S3)
- The probability of **exposure** of each operational situation, from incredible (E0) to high probability (E4)
- The **controllability** of each hazardous event, by the driver or other traffic participants, from controllable in general (C0) to uncontrollable (C3)

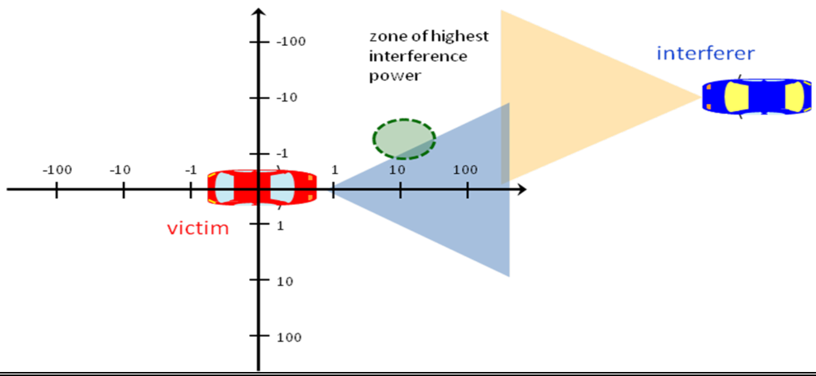
The higher the ASIL level is, the higher level of requirements the safety function needs.

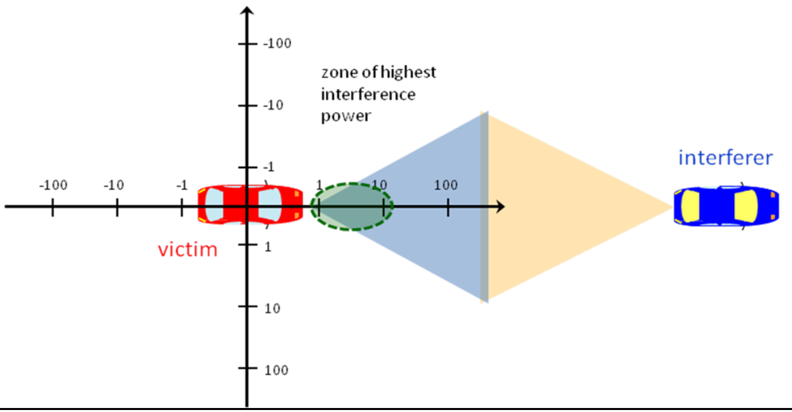
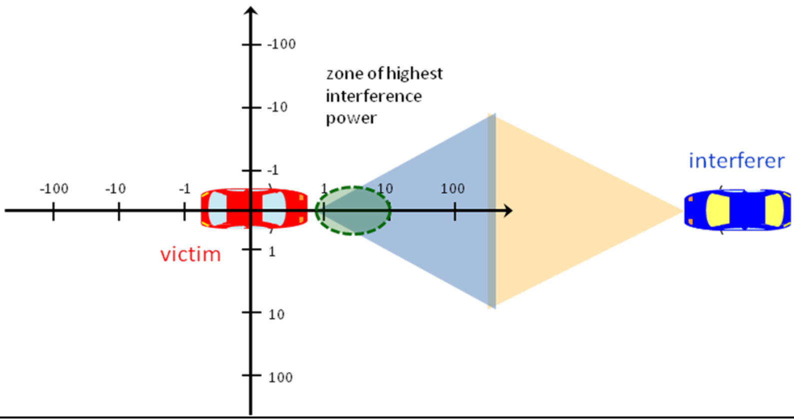
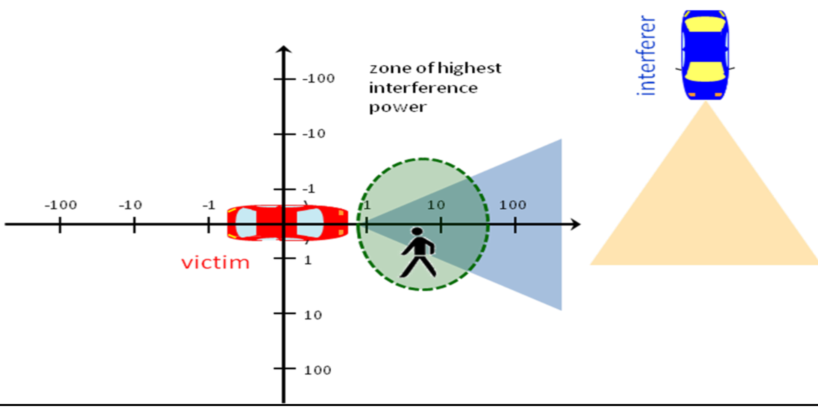
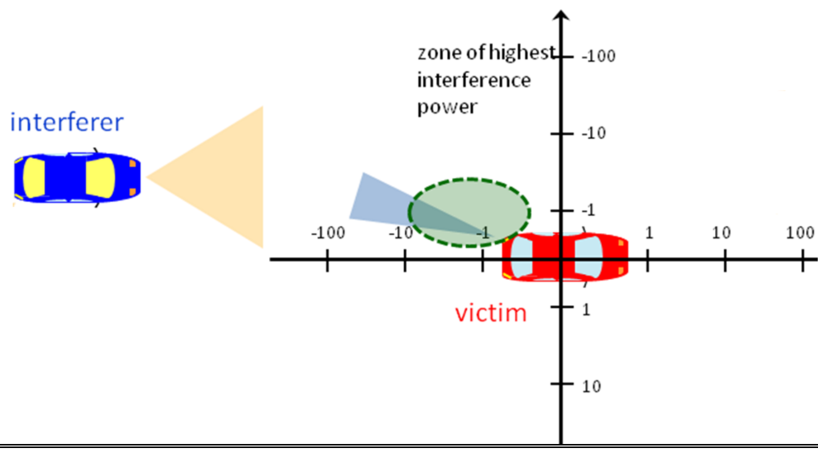
For each function, the level of requirements needed was defined as either mainly low or mainly high. The principle for this discrimination was set to:

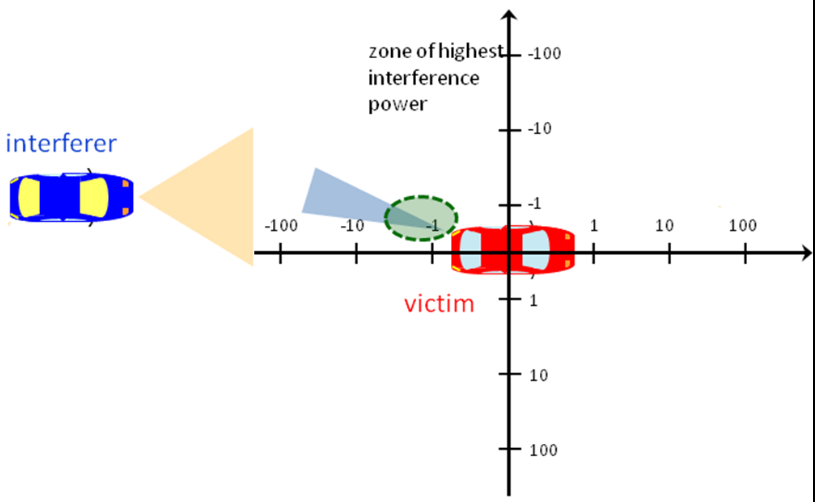
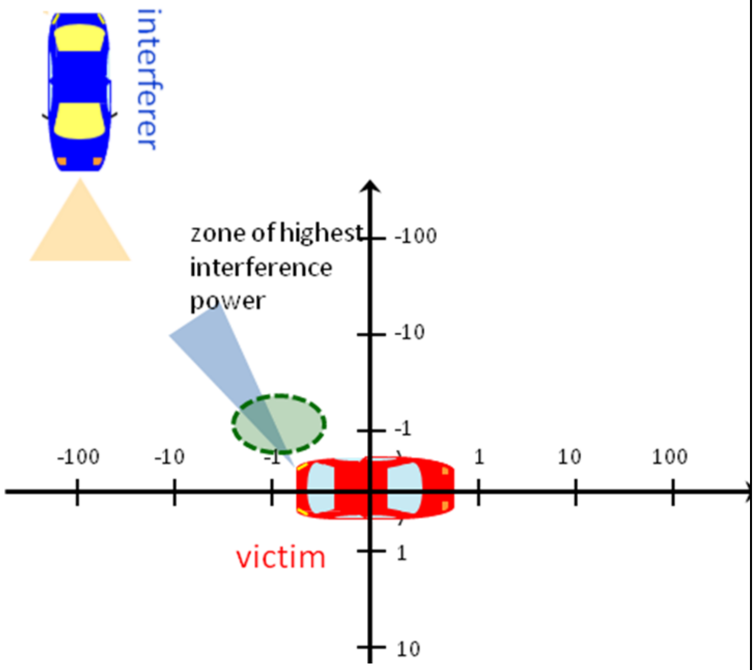
- a function with low level of requirements should be in general controllable (in this case, no ASIL), and can be considered as a comfort function that will only give indications to the driver (e.g. sound alert or visual warning)
- a function with high level of requirements may get an ASIL level (and is considered as a safety function), mainly because it will automatically control the vehicle (i.e. act on the brakes or the steering) and therefore the controllability by the driver is limited.

It can be noted that gradually, even if the function was typically developed to be a comfort function in the beginning, the trend goes towards having more safety-related functions with a higher level of safety requirements.

Yet, comfort functions may still accept a higher level of interference (i.e. a lower level of safety requirements).

N°	Radar Function	Example of interference scenario	Level of requirement needed
1	Adaptive cruise control (ACC)		Mainly high

N°	Radar Function	Example of interference scenario	Level of requirement needed
2	Collision Warning System (CWS)		Mainly low
3	Collision Mitigation System (CMS)		Mainly high
4	Vulnerable road user detection (VUD)		Mainly high
5	Blind Spot Monitoring (BSD)		Mainly low

N°	Radar Function	Example of interference scenario	Level of requirement needed
6	Lane Change Assistance (LCA)		Mainly low
7	Rear crossed traffic alert (RCA)		Mainly low

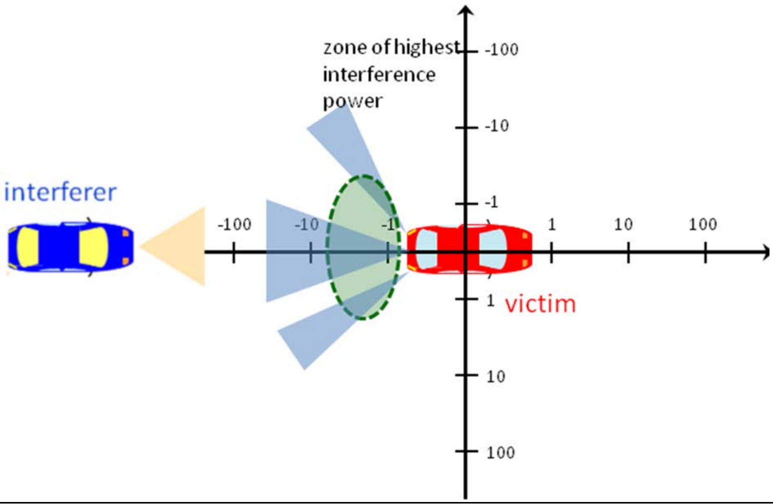
N°	Radar Function	Example of interference scenario	Level of requirement needed
8	Back-up Parking Assist (BPA) or Assisted Parking Systems (APS)		Mainly high

Table 4: List of considered radar applications and level of safety requirements

It is interesting to note that all these radar functions are already available by some of the radar suppliers and have been tested within the project.

4 Applicability of countermeasures to different radar functions

An interesting task in this deliverable was to look at the technical applicability of the different considered countermeasures to the different radar functions, as listed in chapter 3 above.

Aspects to consider are for example

- Minimum frequency bandwidth typically required. Example: Back-up Parking Assist requires a large frequency bandwidth to achiev a sufficiently small range resolution, meaning that countermeasure T6.5 (Detect interference and change frequency range) will not work if frequency bandwidth is limited or too small.
- Minimum timing typically required. Example: Safety functions require continuous measurement updates, meaning that for countermeasure T2.1 (Using random pauses between chirps) the maximum duration of a random pause is limited.

The following Table 5 gives a complete overview of what is feasible for the eight functions considered here. The grey-marked configurations were done either by simulation or best-practice estimation while applicability supported by real measurements is left unmarked.

Note:

Besides the eight functions listed in Table 5 meanwhile new applications with functionalities like Lane Keeping Assistance Systems (LKAS) became apparent. Still lacking an official classification criterion for such functions in either higher level requirements (commonly named safety-critcal functions) or low level requirements (commonly named comfort functions) the guideline used within the project consortium is:

- Functions with only warning, alerting or informing content are classified to the group of safety functions with lower requirements (i.e. comfort application).
- Functions with active control on the vehicle are classed to the group of safety functions with higher requirements (i.e. safety-critical applications).

Though, LKAS with active steering control therefore falls into the group of safety functions with higher requirements.

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 5: Applicability of countermeasures to different radar functions

5 Conclusions

Simulations and real test results show that:

- Mutual interference between vehicular radars appears in typical road scenarios but is unlikely to cause harmful malfunction or sensor breakdown.
- Mitigation techniques further improve the sensor robustness and increase the interference to noise margin.
- Not all mitigation techniques are applicable and useful for the existing and future vehicular radar functions.
-

The CFAR as one mitigation technique is more-or-less standard in all the existing radar sensors.

Combination of CFAR with other mitigation techniques will definitively improve the interference mitigation margin and thus the robustness. This will be all the more important for safety-critical applications.

Furthermore, also available in most radar sensors, but not considered as an explicit mitigation technique in this document, is the tracking algorithm in the signal post-processing chain. Such tracking algorithms help to suppress possible short term noise increases or the rarely occurring ghost targets very effectively.

This Deliverable D5.1 is expected to serve as an input document to the tasks 5.2 and 5.3, where guidelines will be developed (i.e. ways forward to test the robustness of the sensor or advises to sensor manufacturers to implement mitigation techniques).

6 Acronyms

ACC	Automatic Cruise Control
APS	Assisted Parking Systems
BPA	Back-up Parking Assist
APS	Assisted Parking Systems
BSD	Blind Spot Detection
CFAR	Constant False Alarm Rate
CMS	Collision Mitigation System
CWS	Collision Warning System
DBF	Digital Beam Forming
LKAS	Lane Keeping Assistance System
FMCW	Frequency Modulated Continuous-wave
LCA	Lane Change assist
MRR	Medium Range radar
NF	Noise Factor
RCA	Rear crossed traffic alert
SRR	Short Range Radar
VUD	Vulnerable road user detection