International Telecommunication Union

ITU-R

Radiocommunication Sector of ITU

Report ITU-R F.2394-0

(11/2016)

Compatibility between point-to-point applications in the fixed service operating in the 71-76 GHz and 81-86 GHz bands and automotive radar applications in the radiolocation service operating in the 76-81 GHz bands

F Series

Fixed service

International Telecommunication Union

Foreword

The role of the Radiocommunication Sector is to ensure the rational, equitable, efficient and economical use of the radio-frequency spectrum by all radiocommunication services, including satellite services, and carry out studies without limit of frequency range on the basis of which Recommendations are adopted.

The regulatory and policy functions of the Radiocommunication Sector are performed by World and Regional Radiocommunication Conferences and Radiocommunication Assemblies supported by Study Groups.

Policy on Intellectual Property Right (IPR)

ITU-R policy on IPR is described in the Common Patent Policy for ITU-T/ITU-R/ISO/IEC referenced in Annex 1 of Resolution ITU-R 1. Forms to be used for the submission of patent statements and licensing declarations by patent holders are available from http://www.itu.int/ITU-R/go/patents/en where the Guidelines for Implementation of the Common Patent Policy for ITU-T/ITU-R/ISO/IEC and the ITU-R patent information database can also be found.

Series of ITU-R Reports

(Also available online at http://www.itu.int/publ/R-REP/en)

Series	Title
BO	Satellite delivery
BR	Recording for production, archival and play-out; film for television
BS	Broadcasting service (sound)
BT	Broadcasting service (television)
F	**Fixed service**
M	Mobile, radiodetermination, amateur and related satellite services
P	Radiowave propagation
RA	Radio astronomy
RS	Remote sensing systems
S	Fixed-satellite service
SA	Space applications and meteorology
SF	Frequency sharing and coordination between fixed-satellite and fixed service systems
SM	Spectrum management

***Note**: This ITU-R Report was approved in English by the Study Group under the procedure detailed in Resolution ITU-R 1.*

Electronic Publication
Geneva, 2017

REPORT ITU-R F.2394-0

Compatibility between point-to-point applications in the fixed service operating in the 71-76 GHz and 81-86 GHz bands and automotive radar applications in the radiolocation service operating in the 76-81 GHz bands

(2016)

Scope

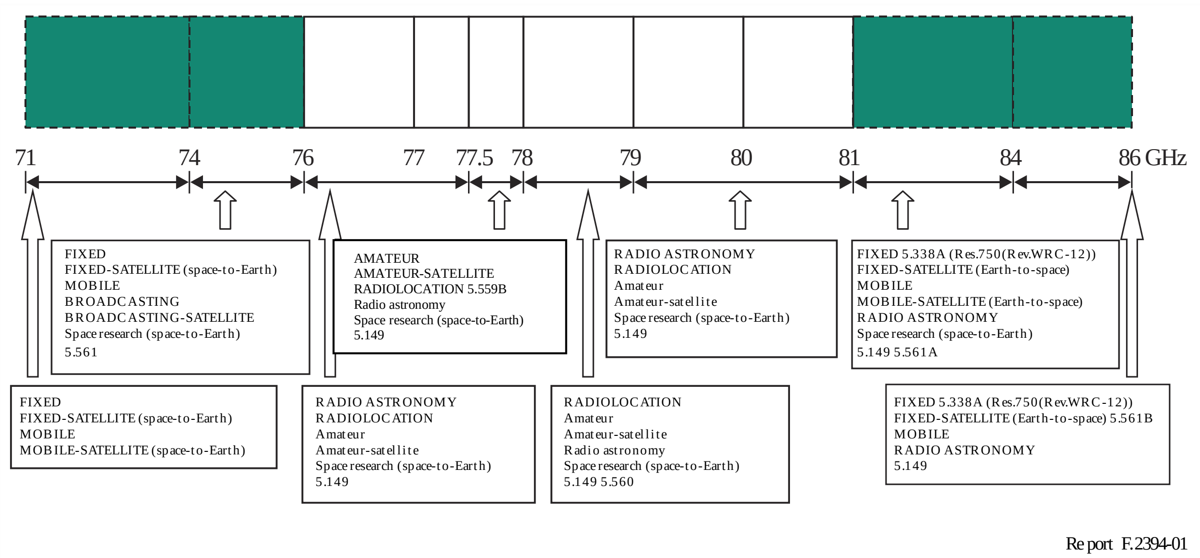
This Report provides the results of the studies, conducted in response to Question ITU-R 252/5, on the compatibility between point-to-point applications in the fixed service operating in the 71-76 GHz and 81-86 GHz bands and automotive radar applications in the radiolocation service operating in the 76-81 GHz bands.

1 Introduction

The frequency bands 76-81 GHz is allocated to the radiolocation service on a primary basis. Various administrations have designated these bands for automotive radar as one application of the radio location service. The adjacent bands of 71-76 GHz and 81-86 GHz are allocated to the fixed service (FS) on a primary basis. Many administrations have designated all or portions of these frequency ranges for short range-high capacity fixed wireless backhaul systems for point-to-point (P-P) applications. These allocations, amongst others, are shown in Fig. 1 below.

FIGURE 1

71-86 GHz spectrum allocation
(Bands allocated to the fixed service are highlighted)



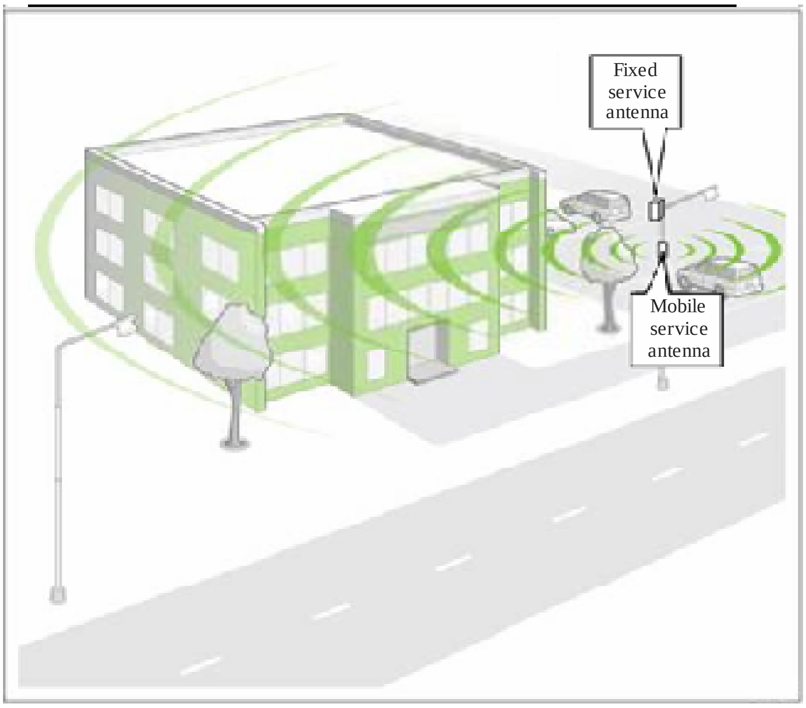
To accommodate the growing demand for mobile broadband services, a developing deployment trend is to reduce the coverage radius of cell sites and increase their proximity to subscribers, mainly in urban areas. This translates in an increase of mobile broadband throughput and/or capacity.

As a means to reduce their distance with subscribers, new base stations are being designed to facilitate mounting on lamp posts and other street level structures. As it is difficult and costly to provide backhaul connections using fibre or Ethernet links to these structures, microwave links are considered as a possible alternative. These links are expected to use panel type directional antennas and small parabolic antennas. The characteristics of the fixed service in the frequency bands 71-76 GHz and 81-86 GHz are well suited to support the current and future requirements of microcellular backhaul networks. The trend of using this frequency range for fixed services is already starting to show in densely populated urban areas with deployment densities up to 1.2 links/km^2 in some parts of Region 2.

Recommendations ITU-R M.1452-2 and ITU-R M.2057-0 provide technical and operational characteristics of automotive radars in the 76-81 GHz frequency band. Due to possible line-of-sight conditions between FS receivers and automotive radar, there is a potential interference. Specifically, as the FS receiving microwave antennas and the automotive radar operate in close proximity, as shown in a deployment example in Fig. 2, there is a need to determine the potential for interference. The current Report is focused on analysing and assessing this potential interference[1] from automotive radar transmitters into FS receivers. The converse compatibility scenario could also be explored in a future study which could analyses and assesses the potential for interference from an FS transmitter into an automotive radar receiver.

FIGURE 2

Potential interference scenario[2]



Report F.2394-02

[1] To minimize the potential adjacent band interference between the fixed service and other services operating in adjacent bands, Recommendation ITU-R F.2006 provides 125 MHz guard bands in the radio frequency channel arrangements at the lower and upper edges of the 71-76 GHz and 81-86 GHz bands. It should be noted however that Recommendation ITU-R F.2006 also provides frequency sub-band or block arrangements, which do not specify any guard bands within the 71-76 GHz and 81-86 GHz bands. Therefore, actual fixed service deployments in these bands within an administration may or may not make use of these guard bands.

2 Assumptions used in the study

2.1 Automotive radar transmitter characteristics

The current study makes use of Recommendations ITU-R M.1452-2 and ITU-R M.2057-0 for the automotive mounted radar transmitter’s specifications to be used in the interference analysis. Tables 1, 2 and 3 below define the technical and operational characteristics of systems operating in the frequency ranges 76 to 77 GHz and 77 to 81 GHz, respectively.

In this Report, automotive radars operating in the frequency bands 76-77 GHz and 77-81 GHz are respectively referred to as long range radars (LRR) and short range radars (SRR). With reference to Table 3, system A provides characteristics for LRR and systems B, C, D, and E provide characteristics for SRR.

TABLE 1

Characteristics of 76-77 GHz LRR (from Recommendation ITU-R M.1452-2)

Characteristic (parameter)	Value
Operational characteristics	
Application	Adaptive cruise control (ACC) ACC stop & go Collision avoidance (CA)
Typical installation	One sensor (behind cooler grill)
Technical characteristics	
Typical range	0-300 m
Frequency range	76.00-77.00 GHz
Specified bandwidth (typical)	Up to 1 GHz
Peak power (e.i.r.p.)	Up to +55 dBm
Mean power (e.i.r.p.)	23.5 to 50 dBm

TABLE 2

Characteristics of 77-81 GHz SRR (from Recommendation ITU-R M.1452-2)

Parameter	Value	
	System A	System B[2]
Mean power spectral density (e.i.r.p.)	+9 dBm/MHz	−3 dBm/MHz (Note 1)
Peak power (e.i.r.p.)	+45 dBm	+55 dBm (Note 2)
Transmit power	+10 dBm	
Antenna gain	35 dBi	
Specified bandwidth	Up to 4 GHz	

NOTE 1 – The maximum mean power spectral density outside a vehicle resulting from the operation of one short-range radar shall not exceed −9 dBm/MHz e.i.r.p.

NOTE 2 – Peak power is defined in 50 MHz bandwidth.

[2] The parameters of System B are derived from ETSI EN 302 264.

In this study, both LRR and SRR transmitted signals are assumed to incur a bumper loss of 6 dB[3]. This factor is shown in Table 2 above with Note 1 and the mean e.i.r.p value for System B. The bumper loss is applied as loss factor along the propagation path from the automotive radar antenna towards its surrounding environment. The incorporation of this factor in the report's calculations is described in § 3.1.

TABLE 3

Characteristics of LRR and SRR (from Recommendation ITU-R M.2057-0)

Parameter	**Radar A[(1)]** **Automotive radar** **For front applications for e.g. for adaptive cruise control**	**Radar B** **Automotive high-resolution radar** **For front applications**	**Radar C** **Automotive high-resolution radar** **For corner applications**	**Radar D** **Automotive high-resolution radar**	**Radar E** **Automotive high-resolution radar** **Very short range applications (e.g. parking-aid, collision avoidance at very low speed)**
Sub-band used (GHz)	76-77	77-81	77-81	77-81	77-81
Typical emission type	FMCW, Fast-FMCW	FMCW, Fast-FMCW	FMCW, Fast-FMCW	FMCW	FMCW, Fast-FMCW
Maximum necessary bandwidth (GHz)	1	4	4	4	4
Maximum e.i.r.p. (dBm)	55	33	33	45	33
Maximum transmit power to antenna (dBm)	10	10	10	10	10
Maximum power density of unwanted emissions (dBm/MHz)	0 (73.5-76 GHz and 77-79.5 GHz) −30 otherwise	−30	−30	−13[(2)]	−30
Antenna main beam gain (dBi)	Typical 30, Maximum 45	TX: 23 RX: 16	TX: 23 RX: 13	TX: 35 max. RX: 35 max	TX: 23 RX: 13
Antenna height (m)	0.3-1 above road	0.3-1 above road	0.3-1 above road	0.3-1 above road	0.3-1 above road
Antenna azimuth scan angle (degrees)	TX/RX: ±15	TX: ±22.5 RX: ±25	TX: ±23 RX: ±30	TX: ±30 RX: ±30	TX: ±50 RX: ±50
Antenna elevation HPBW (degrees)	TX/RX: ±3	TX/RX: ±5.5	TX/RX: ± 5.5	TX/RX: ± 5.5	TX/RX: ± 5.5

3 A similar factor of 6 dB was also used in ECC Report 56 (http://www.erodocdb.dk/docs/doc98/official/pdf/ECCRep056.pdf)

Notes to Table 3:

(1) Radar type A is related to Recommendation ITU-R M.1452.

(2) Maximum power density of unwanted emission is specified at antenna input terminal.
It should be noted that the maximum power density of unwanted emissions specified in Table 3 above is in reference to radiated emissions (e.i.r.p.), with the exception of the value for Radar D which is specified at the antenna input terminal. As for Radar D, the spurious level is practically required to be less than −13 dBm/MHz, which effectively corresponds to an e.i.r.p. value of −30 dBm/MHz, similar to Radar B, C, or E in the spurious domain.

Examples of automotive radar technical limits implementation in the frequency range 76-81 GHz are provided in Annex A.

Finally, it is assumed that the automotive radar transmitters are continuously in operation while the vehicle is in motion or temporarily stopped (e.g. traffic lights), even though the functionality provided by the radars might not be used continuously.

2.2 Automotive radar antenna characteristics

In this study, automotive radar systems are assumed to be designed for the detection of terrain and objects in the horizontal plane, parallel to the ground, surrounding the vehicle. As a result, the maximum radiated emission levels described in § 2.1 would be in a specific azimuth direction within the horizontal plane, and the emission level radiated at a vertical angle towards a FS antenna located above the ground would be reduced by a factor equal to the automotive radar's antenna discrimination factor at the specific angle. For the purpose of this study, the automotive radar antenna gain is assumed to be 30 dBi for LRR and 23 dBi for SRR.

The antenna radiation pattern of LRR is assumed to follow Recommendation ITU-R F.1336-4. This pattern is shown in Fig. 3. The antenna beamwidth parameters required as input by this Recommendation are based on the values obtained from Radars A from Table 3 of this Report, for LRR system.

A specific transmitter antenna radiation pattern, given in Table 4, is used for SRR in the studies.

FIGURE 3

Proposed LRR antenna pattern from F-1336-4

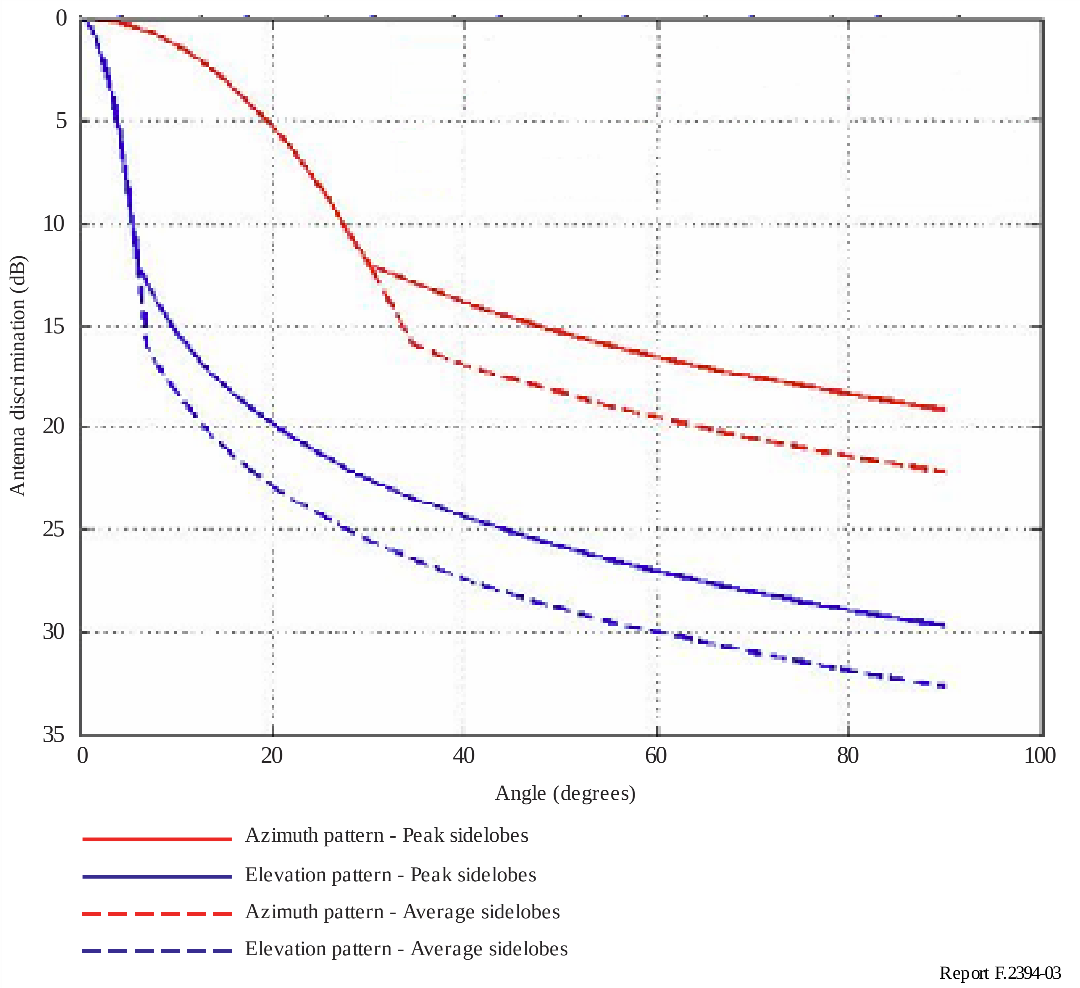


TABLE 4

Specific SRR transmitter antenna radiation pattern

Azimuth Plane		**Elevation Plane**	
Angle (degrees)	Antenna Discrimination (dB down from main lobe)	Angle (degrees)	Antenna Discrimination (dB down from main lobe)
0	0	−90	−96
5	−2.5	−85°	−75
10	−15	−80°	−65
20	−25	−70°	−75
30	−37.5	−60°	−55
35	−35.5	−50°	−55
40	−47	−40°	−55
315	−45	−30°	−55
320	−40	−25	−60
325	−35	−17.5	−50
330	−30	−10	−20
340	−42	−5	−5
345	−22.5	0	0
350	−15	5	−5
355	−2.5	10	−20
360	0	17.5	−50
		20	−70
		25	−60
		30	−55
		40	−50
		50	−60
		60	−55
		70	−55
		80	−55
		85	−80
		90	−95

2.3 Fixed service receiver characteristics

Table 5 below summarizes the technical characteristics and interference protection criteria of FS systems operating in the 71-76 GHz and 81-86 GHz bands to be used in this study.

TABLE 5

Characteristics of fixed service in 71-76 GHz and 81-86 GHz

Parameter	**Value**
Noise power density	−114 dBm/MHz
Noise figure	7 to 11 dB
I/*N* protection criteria	*I*/*N* ≤ −20 dB (Recommendation ITU R F.758-6)
Bandwidth	250 MHz to 5 GHz
Maximum acceptable interference level	−127 to −123 dBm/MHz
Antenna gain	38 to 50 dBi
Antenna radiation pattern	Recommendations ITU R F.699 (for worst-case analysis) or F.1245 (for aggregate or statistical analysis)
Receiver line loss	0 dB
Antenna height	3 to 20 m
Antenna elevation angle	−1 to +5° (typical)[4]

Recommendation ITU-R F.758-6 recommends an *I*/*N* ratio of −20 dB for compatibility studies between adjacent band services, and also provides some considerations for the correlation of rain fading to interference and desired signals § 4.1.2. Therefore, it should be noted that FS links in the 70 GHz frequency range would typically span over very short paths (around 2 km or less), and that the dominant fading mechanism in this frequency range is due to the effects of rain fading with expected correlation. Taking into account both these factors for this specific case, the calculations in this Report use both an *I*/*N* of −20 dB and −10 dB, and the summary results for these are shown in § 4.

Based on the characteristics of Table 5 and above considerations, the threshold for the maximum tolerable interference level at the FS station receiver used in this study are:

$$I_{max,FS} = -114 \text{ dBm/MHz} + (7 \text{ to } 11) \text{ dB} + (-10) \text{ dB} = -117 \text{ to } -113 \text{ dBm/MHz}$$

$$I_{max,FS} = -114 \text{ dBm/MHz} + (7 \text{ to } 11) \text{ dB} + (-20) \text{ dB} = -127 \text{ to } -123 \text{ dBm/MHz}$$

2.4 Fixed service antenna characteristics

As described in Table 5 above, a fixed system antenna gain between 38 and 50 dBi is used in this study. Depending on the relative horizontal and vertical distance between the automotive radar and FS station, the interference received by the FS antenna will arrive at an offset angle with respect to its main beam axis.

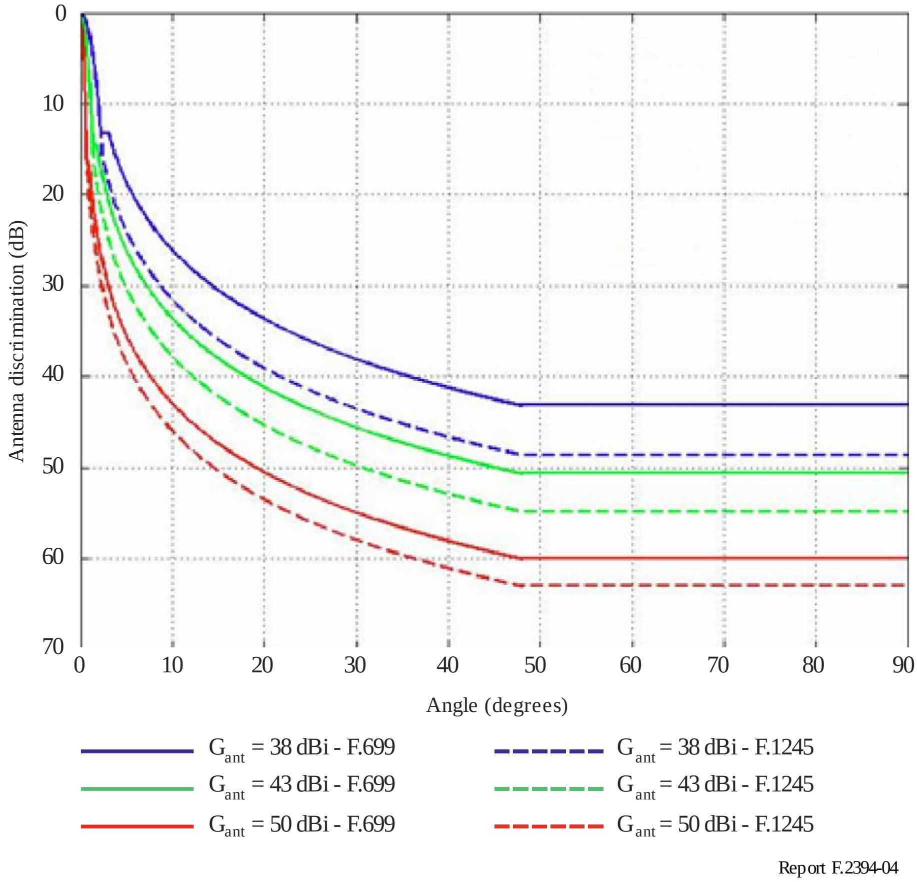
As a result, an antenna discrimination factor with respect to the FS antenna main beam gain is applicable in this study and is determined using Recommendations ITU-R F.699 (for worst-case analysis) and ITU-R F.1245 (for aggregate or statistical analysis). Figure 4 below shows the antenna discrimination factors obtained for different values of FS antenna gain.

---

4 Although the range of antenna elevation angles considered in this study represent typical values, a larger range of elevation angles up from −90 to +90° may be seen in some applications, such as a link between a fixed station mounted on a light pole and the rooftop of a nearby high rise building.

FIGURE 4

Plot of antenna discrimination factor versus angular offset from main beam direction



2.5 Propagation model

This study uses the propagation model described in Recommendation ITU-R P.452 to determine the propagation loss for the automotive radar system's signal, using a smooth circular Earth and a time percentage of 50%. The propagation losses and other parameters used for this model are described in Annex B.

2.6 Interference scenario model

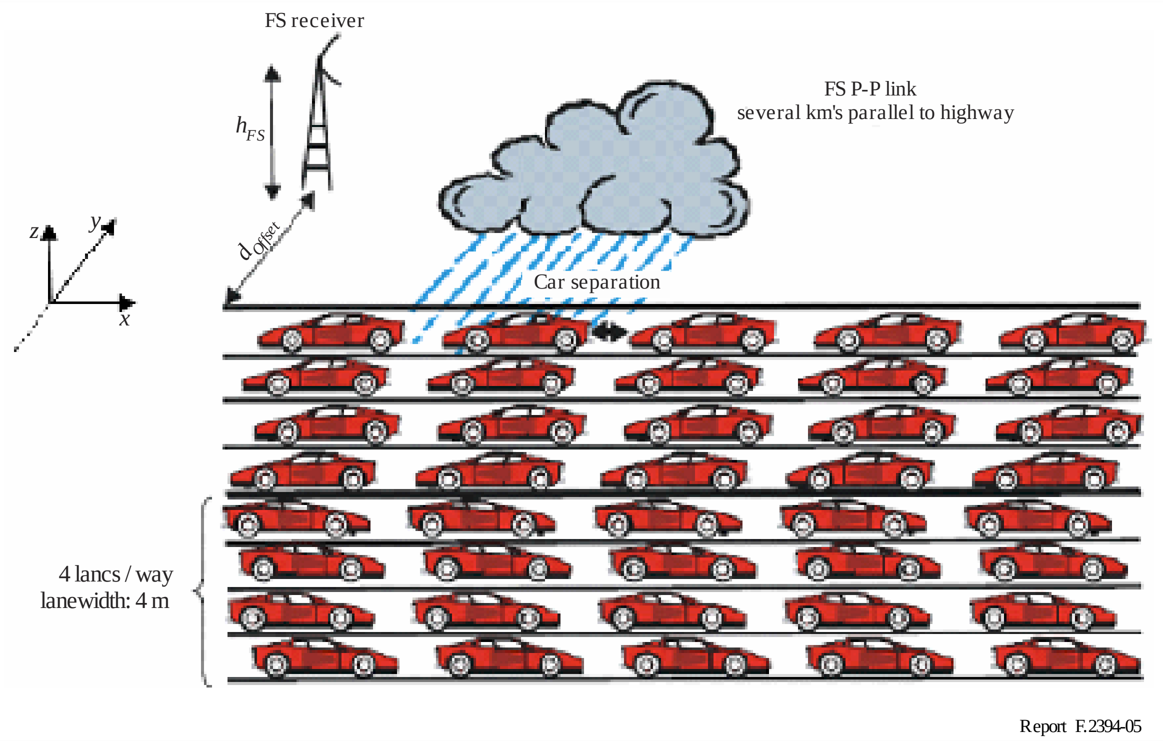
2.6.1 Geometric interference model

The geometric model used to conduct the interference analysis in this study consists of a FS link running in a parallel direction to a multiple lane road. Some of the parameters described in this geometric model are similar to the approach used in Report ITU-R SM.2057 (Annex 2, § 1.5), which studies the impact to the fixed service by automotive radar systems operating around 24 GHz.

Figure 5 provides a schematic representation of this geometric model. While this figure illustrates the interference model for a four-lane highway, other types of roads with one to three lanes (for each direction) are also considered. The interference impact of the automotive radar system is calculated as the car moves through a lane parallel to the path of the FS link, starting in the positive x-axis (i.e. to the right of the FS station) and gradually moving towards the negative part of the x-axis (i.e. to the left of the FS station)[5]. For portions of this study where only a single vehicle is considered, a car placed in the lane closest to the FS station is moved from the positive to the negative part of the x-axis. For portions of this study where multiple vehicles are considered, a single car is again moved through the closest lane, but with additional cars placed in fixed increments in the positive x-axis (i.e. columns) and negative y-axis (i.e. lanes) directions.

FIGURE 5

Schematic representation for interference model (adapted from Report ITU-R SM.2057)



Further details on the geometrical parameters used in the study are described in Annex C.

2.6.2 Vehicle shielding effects[6]

In high volume traffic conditions where multiple vehicles are queuing on roads in close proximity to each other, interference from the automotive radar towards the FS station can be potentially shielded by adjacent vehicles, as illustrated in Fig. 6 below. Report ITU-R SM.2057 (Annex 2, § 1.5.6.5) indicates that losses due to car shielding can be on the order of several 10 dBs for automotive radars operating at 24 GHz. Considering the potentially significant impact that shielding can have on the outcome of this study, it is important to take its effects into account.

In order to properly represent this case, the following shielding loss factors will be used in this study:

$L_{shielding}$ = 0 dB; for calculations considering a single automotive radar

---

[5] This study is focused on the interference scenario of a FS link being parallel to the road, since this scenario is assumed to be the worst case in terms of the maximum distance for which interference could potentially occur.

[6] Cars have been considered in this study, as they provide the least amount of shielding. Trucks could provide more shielding, although this is environment dependent as not all roads allow heavy trucks.

$L_{shielding} = F(\beta - \beta_{AR})$ dB; for calculations considering aggregate interference from multiple automotive radars

where: $F(\beta - \beta_{AR}) = 0$ dB, for $\beta - \beta_{AR} < 0^o$

$F(\beta - \beta_{AR}) = 2.2 \times (\beta - \beta_{AR}) + 4.4$ dB, for $0^o \leq \beta - \beta_{AR} < 8^o$

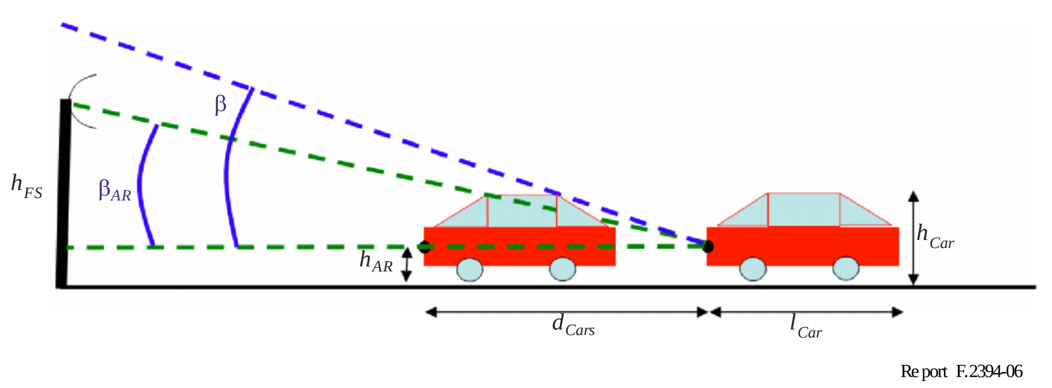
$F(\beta - \beta_{AR}) = 22$ dB, for $\beta - \beta_{AR} \geq 8^o$

and β = minimum elevation angle (in degrees) required for the radar signal path to avoid obstruction by an adjacent vehicle

β_{AR} = elevation angle (in degrees) of radar signal towards the FS antenna.

FIGURE 6

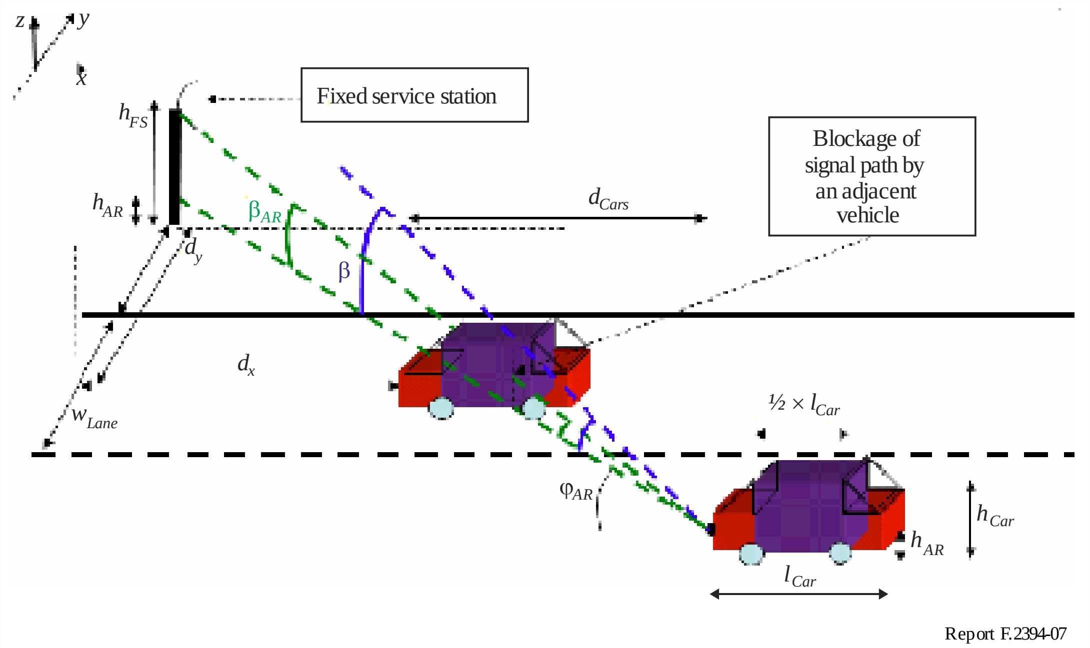
Geometrical sketch of vehicle car shielding from line-of-sight interference between an automotive radar and a FS station



To determine the shielding losses on a single radar transmitter from any surrounding vehicles, the β values are determined for every vehicle which obstructs the path between the automotive radar and the FS antenna in the azimuth plane. To simplify and reduce the computational complexities related to determining the blockage for every radar signal path with surrounding vehicles, the roof of each car is assumed to take a simple rectangular shape with a length equal to half the car's total length. Furthermore, only the central half of each car is considered to determine blockage, as illustrated below in Fig. 7 by the purple-coloured rectangular portion of each car. This simplification is expected to have negligible impact on the shielding loss calculations, since most cases of shielding by the vehicle (including hood or trunk) would also include this central portion in the blocking path. Consideration of shielding by trucks in a further investigation would require an increase in computational complexity.

FIGURE 7

Geometrical sketch of signal path blockage between an automotive radar and a surrounding vehicle



2.6.3 Reflection/diffraction from surrounding vehicles

Reflections and diffraction of an automotive radar signal off surrounding vehicles could potentially increase the interference received by an FS station. For example, emissions from an automotive radar antenna mounted on the back of a vehicle could reflect off the front of the vehicle immediately preceding it and back towards the FS station, and hence add to the aggregate interference produced by multiple cars. However, losses incurred from the reflection of this signal would result in the field strength of this reflected wave at the FS station to be less than the field strength of the wave emitted directly by the automotive radar mounted on the front of the reflecting vehicle (except only in high density traffic conditions where the direct signal of the preceding car is being shielded).

In the studies conducted between automotive radar and fixed service at 24 GHz in Report ITU-R SM.2057 (§ 1.5.6.7), measurements and analysis on these reflection effects found that its impacts can be considered as negligible in comparison to the overall aggregate interference produced by multiple automotive radars.

Furthermore, it is expected that since radio wavelengths are shorter at 76-81 GHz than at 24 GHz, diffraction of a radio wave around a similar-sized metallic object (car) is expected to be less pronounced[7], while reflection of a radio wave off the same metallic object is expected to be more pronounced.

Considering the above arguments, the overall effect of reflection and diffraction effects from surrounding vehicles are assumed to be negligible and will not be taken into account in this study.

2.6.4 Positioning of automotive radar antennas on vehicles

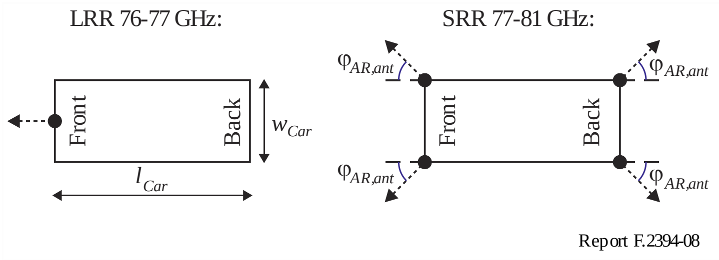
The positioning and orientation of the automotive radar antennas on a vehicle is another factor which is important to determine the antenna discrimination angles and any shielding losses for each automotive radar interference path. In this study, each vehicle is assumed to have a single automotive radar transmitter which operates in 76-77 GHz (LRR) on its central front, and up to four automotive

[7] Use of the monogram in Fig. 3 of Recommendation ITU-R P.526-13 (11/2013) “Propagation by diffraction” shows that an increase in frequency for a given distance results in a lower diffraction loss.

radar transmitters which operate in 77-81 GHz (SRR) placed at each corner of the vehicle. The positioning and main beam orientations of these transmitters are illustrated in Fig. 8. The typical azimuth offset of the SRR main beam against the forward axis of the vehicle ($\varphi_{AR,ant}$) is assumed to be 45º. However, this angle is expected to potentially vary from one deployment scenario to another.

FIGURE 8

Geometrical sketch of automotive radar antenna position and direction for one vehicle



3 Calculations

3.1 Calculation methodology for single entry interference

In determining the interference power received by the FS station from a single vehicle mounted with an automotive radar transmitter, a methodology based on the unwanted emission levels of the automotive radar is considered. This methodology uses the following equation and technical parameters:

$$I = \text{e.i.r.p.}_{AR,\ OOB} - D_{AR}(\alpha_{AR}) - L_{bumper} - L_P - L_{shielding} + G_{FS} - D_{FS}(\alpha_{FS})$$

where:

e.i.r.p.$_{AR,\ OOB}$: is the unwanted e.i.r.p. density emitted by the automotive radar in its main beam direction and is equal to 0 dBm/MHz for automotive radar operating in the band 76-77 GHz and −30 dBm/MHz for automotive radar operating in the band 77-81 GHz

$D_{AR}(\alpha_{AR})$: is the antenna discrimination, in dB, of the automotive radar antenna in the angular direction pointing towards the FS antenna

L_{bumper}: is the bumper loss due to attenuation from the vehicle's frame and is assumed to be 6 dB (as specified in § 2.1)

$L_{shielding}$: is the shielding loss from nearby cars and the methodology used to obtain its values is described in § 2.6.2 of this Report

L_P: is the propagation loss of the automotive radar signal as it arrives at the FS antenna and is calculated using the propagation model described in Recommendation ITU-R P.452, with further details provided in § 2.5 of this Report

G_{FS} is the main beam antenna gain of the FS antenna in dBi

$D_{FS}(\alpha_{FS})$ is the antenna discrimination, in dB, of the FS antenna in the angular direction pointing towards the automotive radar antenna.

3.2 Calculation methodology for aggregate interference

The calculation methodology for the aggregate interference analysis is similar to the single entry analysis, except that the interference from the radar transmitters on each car needs to be considered.

The following formula can then be used to determine to total aggregate interference entire the FS station:

$$I_{Total} = 10 \times \log_{10}\left(\sum 10^{I_i/10}\right)$$

where the summation represents the addition of the interference power I_i produced by each radar transmitter mounted on each vehicle.

4 Results

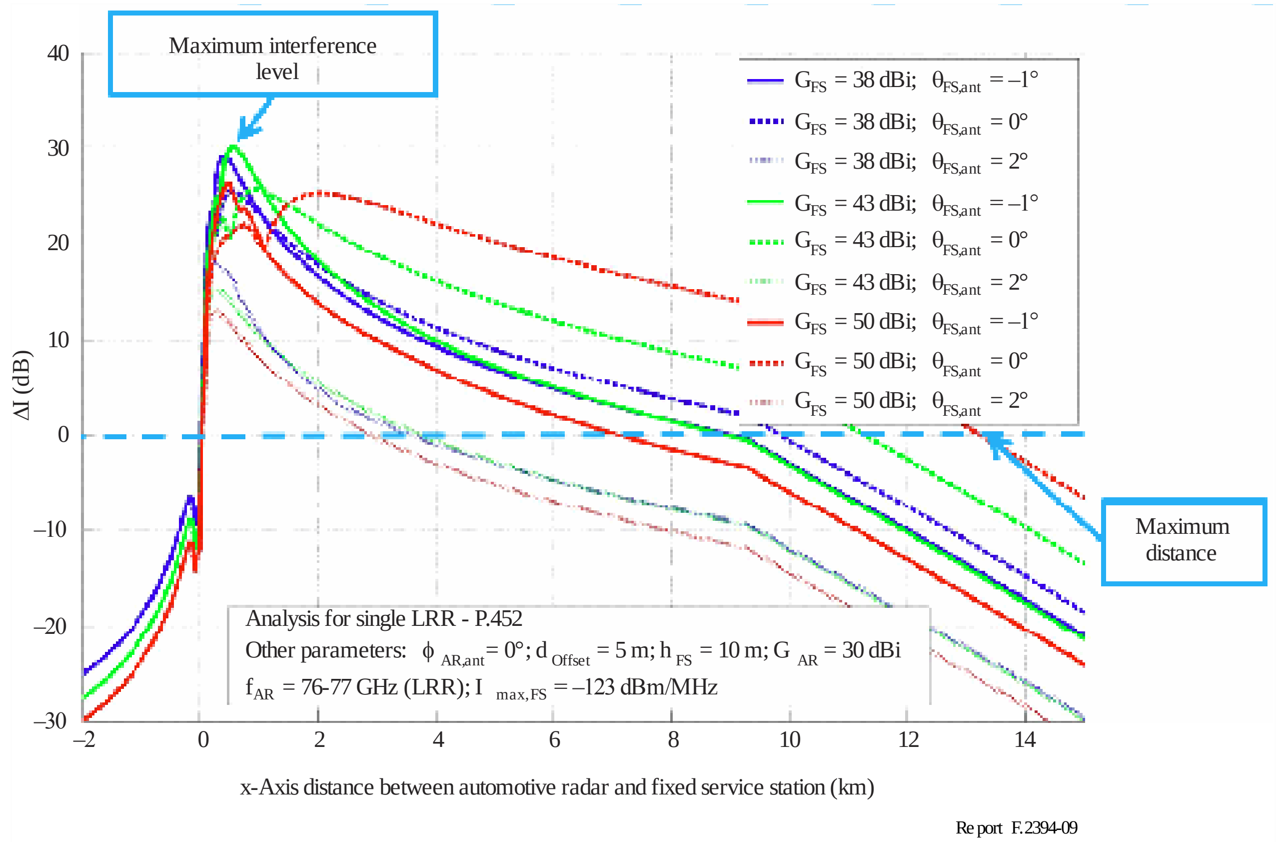
Calculations have been done for four different cases:

1) potential interference from a single vehicle for LRR
2) potential interference from a single vehicle for SRR
3) aggregate interference from multiple vehicles for LRR
4) aggregate interference from multiple vehicles for SRR.

The detailed calculation results, which are presented in Annex D, are in the form of graphs as shown in the representative example in Fig. 9 below. The parameter plotted along the vertical axis is ΔI, which is the difference in the interference level received by the FS station and its maximum interference threshold. Positive values of ΔI indicate that the interference level exceeds the threshold value, and is therefore potentially harmful. The highest value of ΔI represents the maximum level of potential interference. The parameter plotted along the horizontal axis is d_x, the x-axis distance from the FS station to the LRR or SRR interferer(s). The x-Axis value at which a line crosses the zero value of ΔI (y-Axis) represents the maximum distance at which the potential interference can occur. In the single LRR and SRR cases, it is the distance between the FS antenna and the vehicle. For the aggregate LRR and SRR cases, it is the distance between the FS station and the first column of cars, with each adjacent column located at a distance d_{cars} from the previous column. The text boxes within the graphic provide the specific combinations of the parameters being varied and the ones being kept static.

FIGURE 9

Representative example of the graphs presenting the calculation results



The graphical presentation given in Fig. 9 is made with $I/N = -20$ dB. The application of $I/N = -10$ will obviously move the zero ΔI reference up by 10 dB.

With reference to the radar system parameters of Table 3, the results for LRR systems correspond to radar system A, while the results for the SRR systems correspond to radar systems B and C. Assuming similar antenna radiation patterns, the results for SRR systems have also been used to estimate results for radar systems D and E because of the slight difference in the unwanted e.i.r.p. emissions.

In addition, the results are shown for a FS having a noise figure of 11 dB and as a maximum interference threshold ($I_{max,FS}$) of −123 dBm/MHz. The results for an FS having a different noise figure could be extrapolated by adding the difference in noise figure (e.g. add 4 dB for a noise figure of 7 dB).

In order to lighten the main body of this Report, a summary of the calculation results from Annex D are presented in Tables 6 to 9 in the following sections. For the single LRR and SRR interferer cases, a parametric analysis was carried out whereby the FS antenna gain (G_{FS}) was varied while also varying one of the following parameters: FS antenna height (h_{FS}), FS antenna elevation angle ($\theta_{FS,ant}$) and FS antenna distance from the road (d_{offset}). For every combination of parameters investigated (i.e. FS antenna gain and one of the previously listed parameters), the table identifies the highest level of potential interference for a given antenna gain and the worst case level of the parameter being varied. In a similar fashion, the maximum distance at which interference could occur is identified, for the worst case of the parameter being varied. The same approach is taken for the multiple LRR and SRR interferers' cases. However, the following additional cases were investigated due to the presence of multiple vehicles:

– Fixed service's antenna gain (G_{FS}) was varied while varying the distance between cars (d_{cars})

– Fixed service's antenna height (h_{FS}) was varied while varying one of the following parameters: road's number of lanes (n_{lanes}), number of cars per lane ($n_{cars/lane}$) and distance between cars (d_{cars})

– Distance between cars (d_{cars}) was varied while varying the number of cars per lane ($n_{cars/lane}$)

As per § 2.3, all the tables show the highest level of potential interference for both values of *I*/*N* of −20 dB and −10 dB. Positive values of maximum level of potential interference (MAX LEVEL (Δ*I*)) are highlighted for easy reference.

4.1 Results for single entry interference

4.1.1 Results for automotive radars operating in the band 76-77 GHz (LRR)

Table 6 summarizes the detailed results for a single LRR interferer, which are presented in Annex D.

TABLE 6

Single interferer summary results for LRR

LRR single entry interference							
Parameters' combination		**Potential interference case (for *I*/*N* of −20 and −10 dB)**					
		Maximum Level			**Maximum Distance**		
		***I*/*N* = −20 dB**	***I*/*N* = −10 dB**		***I*/*N* = −20 dB**	***I*/*N* = −10 dB**	
FS antenna gain (G_{FS}) and height (h_{FS}) Other parameters: $\theta_{FS,ant}$ (−1°), d_{offset} (5 m)	G_{FS} (dBi)	MAX LEVEL Δ*I* (dB)		h_{FS} value (m)	MAX DISTANCE (km)		h_{FS} value (m)
	50	**30**	**20**	20	7.5	3	20
	43	**30**	**20**	10	9.5	4.6	20
	38	**30**	**20**	3	9.2	4	20
FS antenna gain (G_{FS}) and offset distance from road d_{offset} Other parameters: $\theta_{FS,ant}$ (−1°), h_{FS} (10 m)	G_{FS} (dBi)	MAX LEVEL Δ*I* (dB)		d_{offset} value (m)	MAX DISTANCE (km)		d_{offset} value (m)
	50	**27**	**17**	5	7	3	All/5&10[1]
	43	**30**	**20**	5	9.2	4	All/5&10[1]
	38	**29**	**19**	5	9.2	3.8	All
FS antenna gain (G_{FS}) and elevation angle $\theta_{FS,ant}$ Other parameters: h_{FS} (10 m), d_{offset} (5 m)	G_{FS} (dBi)	MAX LEVEL Δ*I* (dB)		$\theta_{FS,ant}$ value (°)	MAX DISTANCE (km)		$\theta_{FS,ant}$ value (°)
	50	**26**	**16**	0	13.1	10.5	0
	43	**30**	**20**	−1	11.2	7.1	0
	38	**29**	**19**	−1	9.9	4.6	0

NOTE 1 – The value before the "/" sign applies to an *I*/*N* of −20 dB and the values following the "/" sign apply to an *I*/*N* of −10 dB.

The calculation results for the scenario described in Table 6 show that the interference level gradually increases as the LRR approaches the FS station within the axis corresponding to its azimuth direction (maximum interference is 30 dB above the threshold and interference can potentially occur up to 13.1 km away from the FS antenna in the worst case). This trend is observed mainly due to the decreasing propagation losses as separation distance decreases, while the local reductions in the trend are caused by the counteracting effect of increasing antenna discrimination factors at shorter distances. As a result, the precise distance at which the maximum interference level occurs is also strongly dependant on the FS station antenna gain, its pattern and its height. Also, an FS station installed away from the road (offset distance) decreases the potential for interference when the LRR is at short distances. Finally, due to antenna narrow beamwidth at this frequency range, even small elevation angle changes have an impact to the potential interference level and distance.

4.1.2 Results for automotive radars operating in the band 77-81 GHz (SRR)

Table 7 summarizes the detailed results for a single SRR interferer, which are presented in Annex D. Overall, the results indicate no potential for harmful interference from a single vehicle's SRRs as long as the automotive radar's horizontal plane angle $\varphi_{AR,ant}$ is 45° for either cases of I/N values. Although the SRR radar antenna would be geometrically arranged to have an angle of 45° relative to the road (see Fig. 8), a worst case scenario of 0° has been added in the last row's combination of parameters to show its potential impact. This has been added as the angle is expected to potentially vary from one deployment scenario to another. If $\varphi_{AR,ant}$ would be 0°, then a potential for interference would exist only for an I/N protection criterion of −20 dB.

TABLE 7

Single interferer summary results for SRR

SRR single entry interference							
Parameters' combination		**Potential interference case (for I/N of −20 and −10 dB)**					
		Maximum Level			**Maximum Distance**		
		I/N = −20 dB	**I/N = −10 dB**		**I/N = −20 dB**	**I/N = −10 dB**	
FS antenna gain (G_{FS})and height (h_{FS}) Other parameters: $\theta_{FS,ant}$ (−1°), d_{offset} (5 m), $\varphi_{AR,ant}$ (45°)	G_{FS} (dBi)	MAX LEVEL ΔI (dB)		h_{FS} value (m)	MAX DISTANCE (km)		h_{FS} value (m)
	50	−7.5	−17.5	3&10	N/A	N/A	N/A
	43	−5	−15	3&10	N/A	N/A	N/A
	38	−3	−13	3&10	N/A	N/A	N/A
FS antenna gain (G_{FS}) and offset distance from road d_{offset} Other parameters: $\theta_{FS,ant}$ (−1°), h_{FS} (10 m), $\varphi_{AR,ant}$ (45°)	G_{FS} (dBi)	MAX LEVEL ΔI (dB)		OFFSET value (m)	MAX DISTANCE (km)		OFFSET value(m)
	50	−7.5	−17.5	5	N/A	N/A	N/A
	43	−5	−15	5	N/A	N/A	N/A
	38	−3	−13	5	N/A	N/A	N/A
FS antenna gain (G_{FS}) and elevation angle $\theta_{FS,ant}$ Other parameters: h_{FS} (10 m), d_{offset} (5 m), $\varphi_{AR,ant}$ (45°)	G_{FS} (dBi)	MAX LEVEL ΔI (dB)		$\theta_{FS,ant}$ value (°)	MAX DISTANCE (km)		$\theta_{FS,ant}$ value (°)
	50	−7	−17	−1	N/A	N/A	N/A
	43	−5	−15	−1	N/A	N/A	N/A
	38	−3	−13	−1	N/A	N/A	N/A
FS antenna gain (G_{FS}) and radar antenna azimuth angle ($\varphi_{AR,ant}$) Other parameters: $\theta_{FS,ant}$ (−1°), h_{FS} (10 m), d_{offset} (5 m)	G_{FS} (dBi)	MAX LEVEL ΔI (dB)		$\varphi_{AR,ant}$ value (°)	MAX DISTANCE (km)		$\varphi_{AR,ant}$ value(°)
	50	−2	−12	0	N/A	N/A	N/A
	43	**3**	−7	0	0.9	N/A	0
	38	**2**	−8	0	0.6	N/A	0

4.2 Results for aggregate interference

4.2.1 Results for automotive radars operating in the band 76-77 GHz (LRR)

Table 8 summarizes the detailed results which are presented in Annex D.

TABLE 8

Aggregate interferers' summary results for LRR

LRR aggregate interference							
Parameters' combination		**Potential interference case (for *I*/*N* of −20 and −10 dB)**					
		Maximum Level			**Maximum Distance**		
		***I*/*N* = −20 dB**	***I*/*N* = −10 dB**		***I*/*N* = −20 dB**	***I*/*N* = −10 dB**	
FS antenna gain (G_{FS}) and height (h_{FS}) Other parameters: $\theta_{FS,ant}$ (−1°), d_{offset} (5 m), d_{cars} (50 m), n_{lanes} (3), $n_{cars/lane}$ (100)	G_{FS} (dBi)	MAX LEVEL Δ*I* (dB)		h_{FS} value (m)	MAX DISTANCE (km)		h_{FS} value (m)
	50	**38**	**28**	20	9.5	4.6	20
	43	**40**	**30**	20	14.2	7.1	20
	38	**39**	**29**	20	14.2	6.7	20
FS antenna gain (G_{FS}) and offset distance from road d_{offset} Other parameters: $\theta_{FS,ant}$ (−1°), h_{FS} (10 m), d_{cars} (50 m), n_{lanes} (3), $n_{cars/lane}$ (100)	G_{FS} (dBi)	MAX LEVEL Δ*I* (dB)		d_{offset} value (m)	MAX DISTANCE (km)		d_{offset} value (m)
	50	**35**	**25**	5	9.1	3.8	All
	43	**38**	**28**	5	10.8	6.5	All
	38	**40**	**30**	5	10.9	6.5	All
FS antenna gain (G_{FS}) and elevation angle $\theta_{FS,ant}$ Other parameters: h_{FS} (10 m), d_{offset} (5 m), d_{cars} (50 m), n_{lanes} (3), $n_{cars/lane}$ (100)	G_{FS} (dBi)	MAX LEVEL Δ*I* (dB)		$\theta_{FS,ant}$ value (°)	MAX DISTANCE (km)		$\theta_{FS,ant}$ value (°)
	50	**35**	**25**	−1	15	12.1	0
	43	**38**	**28**	−1	13	10.1	0
	38	**40**	**30**	−1	11.7	7.8	0
FS antenna gain (G_{FS}) and distance between cars (d_{cars}) Other parameters: $\theta_{FS,ant}$ (−1°), h_{FS} (10 m), n_{lanes} (3), $n_{cars/lane}$ (100)	G_{FS} (dBi)	MAX LEVEL Δ*I* (dB)		d_{cars} value (m)	MAX DISTANCE (km)		d_{cars} value (m)
	50	**35**	**25**	50	9	3.8	50
	43	**38**	**28**	50	10.9	6.4	50
	38	**40**	**30**	50	10.9	6.4	50
FS antenna height (h_{FS}) and number of lanes (n_{lanes}) Other parameters: $\theta_{FS,ant}$ (−1°), G_{FS} (38 dBi), d_{offset} (5 m), $n_{cars/lane}$ (100), d_{cars} (50 m)	h_{FS} (m)	MAX LEVEL Δ*I* (dB)		n_{lanes} value	MAX DISTANCE (km)		n_{lanes} value
	20	**40**	**30**	3	14.3	6.7	3
	10	**40**	**30**	3	10.9	6.4	3
	3	**37.5**	**27.5**	3	6.9	4.8	3
FS antenna height (i) and number of cars per lane ($n_{cars/lane}$) Other parameters: $\theta_{FS,ant}$ (−1°), G_{FS} (38 dBi), d_{offset} (5 m), n_{lanes} (3), d_{cars} (50m)	h_{FS} (m)	MAX LEVEL Δ*I* (dB)		$n_{cars/lane}$ value	MAX DISTANCE (km)		$n_{cars/lane}$ value
	20	**40**	**30**	100&500	14.4	6.7	All
	10	**40**	**30**	100&500	10.8	6.4	All
	3	**37.5**	**27.5**	All	6.8	4.8	All
Distance between cars (d_{cars}) and number of cars per lane ($n_{cars/lane}$) Other parameters: $\theta_{FS,ant}$ (−1°), h_{FS} (10 m), d_{offset} (5 m), G_{FS} (38 dBi), n_{lanes} (3)	d_{cars} (m)	MAX LEVEL Δ*I* (dB)		$n_{cars/lane}$ value	MAX DISTANCE (km)		$n_{cars/lane}$ value
	50	**40**	**30**	100&500	10.9	6.4	All
	20	**33**	**23**	100&500	10.6	6	All
	10	**32**	**22**	All	10.5	5.8	All
FS antenna height (h_{FS}) and distance between cars (d_{cars}) Other parameters: $\theta_{FS,ant}$ (−1°), G_{FS} (38 dBi), d_{offset} (5 m), $n_{cars/lane}$ (100), n_{lanes} (3)	h_{FS} (m)	MAX LEVEL Δ*I* (dB)		d_{cars} value (m)	MAX DISTANCE (km)		d_{cars} value (m)
	20	**40**	**30**	50	14.3	6.7	50
	10	**40**	**30**	50	10.9	6.3	50
	3	**38**	**28**	50	6.7	4.7	50

In summary, the aggregate interference from multiple vehicles having LRRs significantly raises the maximum interference, compared to that of the single entry case, which would be received by an FS station, with the interference level results in the study up to 40 dB above the threshold (10 dB higher than for the single-entry LRR case). However, in comparison to the single entry interference case, the maximum distance for potential interference is only marginally increased to up to 15 kilometres for aggregate interference, mainly due to vehicular shielding effects. Generally:

– FS station with higher h_{FS}, lower d_{offset}, lower $\theta_{FS,ant}$, and generally lower G_{FS} result in the higher interference levels.
– A lower density of cars (i.e. higher d_{cars}) results in the worst case interference conditions.
– A larger n_{lanes} results in greater interference (with the effects more pronounced at high h_{FS}).
– Increasing the total number of interferers in a lane $n_{cars/lane}$ has only a small impact on the maximum interference.

4.2.2 Results for automotive radars operating in the band 77-81 GHz (SRR)

Table 9 summarizes the detailed results which are presented in Annex D.

TABLE 9

Aggregate interferers' summary results for SRR

SRR aggregate interference							
Parameters' combination		**Potential interference case (for *I/N* of −20 and −10 dB)**					
		Maximum Level			**Maximum Distance**		
		***I/N* = −20 dB**	***I/N* = −10 dB**		***I/N* = −20 dB**	***I/N* = −10 dB**	
FS antenna gain (G_{FS}) and height (h_{FS})	G_{FS} (dBi)	MAX LEVEL ΔI (dB)		h_{FS} value (m)	MAX DISTANCE (km)		h_{FS} value (m)
Other parameters: $\theta_{FS,ant}$ (−1°), $\varphi_{AR,ant}$ (45°), d_{offset} (5 m), d_{cars} (50 m), n_{lanes} (3), $n_{cars/lane}$ (100)	50	−5.5	−15.5	20	N/A	N/A	N/A
	43	−4	−14	20	N/A	N/A	N/A
	38	−3	−13	20	N/A	N/A	N/A
FS antenna gain (G_{FS}) and offset distance from road d_{offset}	G_{FS} (dBi)	MAX LEVEL ΔI (dB)		d_{offset} value (m)	MAX DISTANCE (km)		d_{offset} value (m)
Other parameters: $\theta_{FS,ant}$ (−1°), $\varphi_{AR,ant}$ (45°), h_{FS} (10 m), d_{cars} (50 m), n_{lanes} (3), $n_{cars/lane}$ (100)	50	−4	−14	All	N/A	N/A	N/A
	43	−5	−15	All	N/A	N/A	N/A
	38	−7	−17	All	N/A	N/A	N/A
FS antenna gain (G_{FS}) and elevation angle $\theta_{FS,ant}$	G_{FS} (dBi)	MAX LEVEL ΔI (dB)		$\theta_{FS,ant}$ value (°)	MAX DISTANCE (km)		$\theta_{FS,ant}$ value (°)
Other parameters: $\varphi_{AR,ant}$ (45°), h_{FS} (10 m), d_{offset} (5m), d_{cars} (50 m), n_{lanes} (3), $n_{cars/lane}$ (100)	50	−5.5	−15.5	All	N/A	N/A	N/A
	43	−4.5	−14.5	All	N/A	N/A	N/A
	38	−3	−13	All	N/A	N/A	N/A
FS antenna gain (G_{FS}) and distance between cars (d_{cars})	G_{FS} (dBi)	MAX LEVEL ΔI (dB)		d_{cars} value (m)	MAX DISTANCE (km)		d_{cars} value (m)
Other parameters: $\theta_{FS,ant}$ (−1°), $\varphi_{AR,ant}$ (45°), h_{FS} (10 m), d_{offset} (5 m), n_{lanes} (3), $n_{cars/lane}$ (100)	50	−1	−11	All	N/A	N/A	N/A
	43	**0.5**	−9.5	All	0.1	N/A	10
	38	**2**	−8	All	0.1	N/A	10
FS antenna height (h_{FS}) and number of lanes (n_{lanes})	h_{FS} (m)	MAX LEVEL ΔI (dB)		n_{lanes} value	MAX DISTANCE (km)		n_{lanes} value
Other parameters: $\theta_{FS,ant}$ (−1°), $\varphi_{AR,ant}$ (45°), G_{FS} (43 dBi), d_{offset} (5 m), $n_{cars/lane}$ (100), d_{cars} (50 m)	20	−4	−14	3	N/A	N/A	N/A
	10	−4	−14	3	N/A	N/A	N/A
	3	−10	−20	All	N/A	N/A	N/A

TABLE 9 (*end*)

SRR aggregate interference							
Parameters' combination		**Potential interference case (for *I*/*N* of −20 and −10 dB)**					
		Maximum Level			**Maximum Distance**		
		***I*/*N* = −20 dB**	***I*/*N* = −10 dB**		***I*/*N* = −20 dB**	***I*/*N* = −10 dB**	
FS antenna height (h_{FS}) and number of cars/lane ($n_{cars/lane}$) Other parameters: $\theta_{FS,ant}$ (−1°), $\varphi_{AR,ant}$ (45°), d_{cars} (50 m), d_{offset} (5 m), G_{FS} (43 dBi), n_{lanes} (3)	h_{FS} (m)	MAX LEVEL ΔI (dB)		$n_{cars/lane}$ value	MAX DISTANCE (km)		$n_{cars/lane}$ value
	20	−4.5	−14.5	All	N/A	N/A	N/A
	10	−4.5	−14.5	All	N/A	N/A	N/A
	3	−7	−17	All	N/A	N/A	N/A
Distance between cars (d_{cars}) and number of cars/lane ($n_{cars/lane}$) Other parameters: $\theta_{FS,ant}$ (−1°), $\varphi_{AR,ant}$ (45°), h_{FS} (10 m), d_{offset} (5 m), G_{FS} (43Bi), n_{lanes} (3)	d_{cars} (m)	MAX LEVEL ΔI (dB)		$n_{cars/lane}$ value	MAX DISTANCE (km)		$n_{cars/lane}$ value
	50	−5	−15	All	N/A	N/A	N/A
	20	−2	−12	All	N/A	N/A	N/A
	10	**0**	−10	All	0.1	N/A	All
FS antenna height (h_{FS}) and distance between cars (d_{cars}) Other parameters: $\theta_{FS,ant}$ (−1°), $\varphi_{AR,ant}$ (45°), d_{offset} (5 m), G_{FS} (43 dBi), $n_{cars/lane}$ (100), n_{lanes} (3)	h_{FS} (m)	MAX LEVEL ΔI (dB)		d_{cars} value (m)	MAX DISTANCE (km)		d_{cars} value (m)
	20	**0**	−10	All	0.25	N/A	10
	10	**0**	−10	All	0.1	N/A	10
	3	−5	−15	All	N/A	N/A	N/A

In summary, as expected, the aggregate interference from multiple vehicles having SRRs raises the maximum interference signal level which would be received by an FS station. Potential interference cases are only observed for the more stringent protection criterion *I*/*N* of −20 dB. Highest ΔI (2 dB) is encountered with lowest d_{cars} and lowest G_{FS} when very close to the FS antenna. This happens when the FS antenna is momentarily in the SRR antenna's main beam. Exceedance of the interference criterion is expected to occur for a short duration during normal traffic movement. In practice, however, these interference levels could be momentarily further exceeded in a small probability of cases where the curvature of a road could cause the main beam azimuth angles of the FS and SRR to approach each other.

5 Results discussion and potential mitigation techniques

5.1 Results discussion

Results in section 4 show that potential of interference from automotive radar transmitters into FS receivers is in the case of LRR radars. More specifically:

– The highest level of potential interference calculated is 40 dB above the threshold with multiple LRR for *I*/*N* value of −20 dB.

  • Although the maximum level for potential interference in the aggregate LRR case is significantly greater than the single LRR case (40 dB compared to 30 dB), the maximum distance only increases by a relatively smaller margin (15 km compared to 12.1 km).

– A road with multiple lanes increases the potential for interference, due to the potential for a greater number of radar transmitters. However, a short distance between cars limits the interference potential, due to shielding effects.

– Due to the FS antenna's small beamwidth, the FS antenna height and elevation angle below the horizon have negligible impacts on the potential interference level. However, an FS antenna elevation angle above the horizon can significantly reduce the potential for interference.

  However, because of the same small beamwidth, the distance between the FS antenna and the road has a significant impact, since the automotive radar signal could fall within the FS antenna main lobe.

  • Worst cases are when FS antenna and automotive radar antenna are within each other main lobe.
  • Increasing the FS antenna distance with the road can reduce the potential interference level.

There are limited cases under specific conditions where the SRR radar can potentially cause interference to the fixed service receiver. This happens for multiple SRR at very short distances from the fixed service station, when the SRR main beam can momentarily fall near the fixed service receiver antenna main beam. Even in this case, it is found to apply solely for an I/N of −20 dB. Interference is not expected to occur under typical operating conditions.

It should be noted that the above results described in this study indicate specific potential interference cases based on the evaluation of a selected group of practical scenarios, as well as several assumptions on system parameters and signal propagation. Furthermore, this study does not investigate the statistical likelihood of these potential interference scenarios, nor their detailed impact on the FS communication link.

5.2 Potential mitigation techniques and further activities for improving compatibility

On the topic of possible mitigation techniques, the study helped provide consideration of some aspects to improve the compatibility between both adjacent services, where possible, such as:

– the avoidance of fixed service links pointed in an azimuth direction near to and parallel to the street;
– the avoidance of fixed service antenna pointed in negative elevation angles towards vehicles located on the street;
– for links close to streets, the use of RF channels further away from the band edge.

Additional studies could be conducted to further improve the coexistence of both services, as well as identify additional potential mitigation techniques. Topics for consideration for such new study could involve:

– Use of different polarization by the two services;
– Minimize radar antenna radiation above the horizontal plane, since the goal is to prevent collision with other vehicles or obstacles;
– Investigate further shielding mechanism (see Figs 6 and 7 in § 2.6.2) including cases involving the inclusion of trucks[8] rather than only cars;

[8] The use of more complex vehicular traffic models could help reflect in some cases a more realistic relative composition and physical sizes of vehicles, including large trucks and horizontal spacing of such vehicles relative to vehicle length. Large trucks in the right-hand lane will provide a higher level of shielding between vehicular radar and the fixed service antenna (which is offset from the first lane), especially under environments where a greater proportion of the total traffic is comprised of large trucks and when greater proportion of trucks are using the right-hand lane instead of other lanes.

– Investigate further unwanted emissions from radar transmitter, as the current study considered a flat value outside the radar RF band;

– Investigate potential radar transmitter characteristics and/or parameters that may assist in optimizing compatibility between both adjacent services;

– Investigate the LRR and SRR radars' duty cycle while the vehicle is in motion or temporarily stopped e.g. in front of traffic lights;

– Investigate the converse compatibility scenario analysing the interference impact from a FS transmitter into an automotive radar receiver.

6 Conclusions

This Report focused on the study of the potential for adjacent band interference from automotive radar transmitters into FS radio systems.

Two types of automotive radars have been investigated: long range radars (LRR) operating in the frequency band 76-77 GHz, and short range radars (SRR) operating in the frequency range 77-81 GHz. For each type, cases of potential interference from single automotive radar as well as effects from the aggregation of multiple automotive radars have been studied.

In summary, the results showed that potential interference exists mainly for LRR radar. Use of an I/N of −10 dB reduces both the potential of interference, as well as the maximum distance at which it can happen. Considering that only few potential interference cases were observed solely for an I/N of −20 dB, it is expected that SRR radars would have a marginal impact on a fixed service receiver, as long as the SRR is deployed with its main beam at 45º from the forward axis of the vehicle.

This study has identified practical scenarios that could result in interference levels above the threshold based on a set of parameters and assumptions. This suggests two follow-up actions for consideration for optimal use of both services:

1) the preparation of guidelines in a separate document using this study's results, to develop mitigation techniques ensuring optimal use of both adjacent fixed and radiolocation services;

2) a new study to further investigate ways to optimize coexistence of both adjacent services.

Annex A

Automotive radar technical limits implementation examples in the frequency range 76-81 GHz

In addition to the transmitter characteristics shown in § 2.2, some administrations have adopted, for regulatory purposes, technical limits for automotive radar equipment operating in the frequency bands 76-77 GHz and 77-81 GHz.

Table 10 below identifies the unwanted radiated power spectral density limits adopted by some administrations. These limits are in line with the unwanted emission levels of most automotive radar systems shown in Table 3 above.

TABLE 10

Unwanted emission limits of automotive radar systems operating in the bands 76-77 GHz and 77-81 GHz, adopted by some administrations for regulatory purposes

Automotive radar frequency range	Unwanted e.i.r.p. limit	Standard	Source
76-77 GHz	0 dBm/MHz (mean power)	ETSI EN 301 091	Europe
77-81 GHz	−30 dBm/MHz	ETSI EN 302 264	Europe
76-77 GHz	−1.7 dBm/MHz	FCC Part 15.253	United States of America
76-77 GHz	−1.7 dBm/MHz	RSS-251	Canada

Annex B

Propagation losses and other parameters used for the propagation model described in Recommendation ITU-R P.452

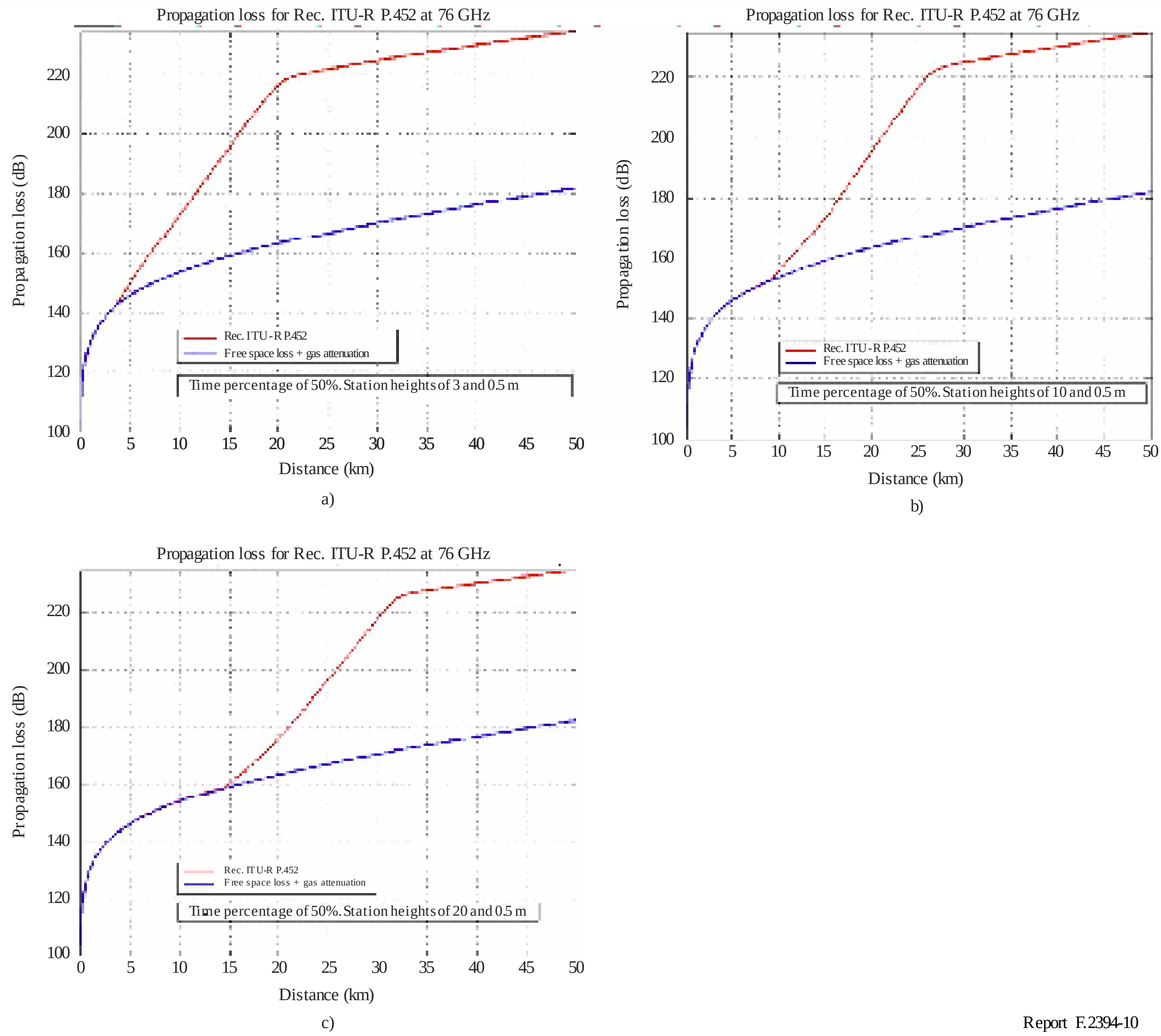
Figure 10 provides the propagation losses used for the calculations conducted in this study. The propagation model described by Recommendation ITU-R P.452 was used, with a time percentage of 50% and the assumption of a smooth circular Earth terrain profile. The station heights and antenna gain values used in this model correspond to the values of antenna heights used for the fixed service and automotive radar stations.

The gaseous absorption loss portion of the propagation losses described by this model are based on information from Recommendations ITU-R P.676 and ITU-R P.835, which provide a factor of 0.36 dB/km around 76 GHz. This application of these factors in this study assumed a ground elevation equal to the median sea level, an air pressure of 1013 hPa, a temperature of 15° C and a water vapour density of 7.5 g/m^3.

Furthermore, the propagation losses provided by the model of Recommendation ITU-R P.452 were set to a minimum value equal to the losses provided by the combination of the free space model and the gaseous absorption component. It is expected that the actual terrain data and other man made obstacles would result in higher losses in most cases.

FIGURE 10

Proposed propagation model losses and other parameters for the study



Annex C

Further details on the geometrical parameters used in the study

Figure 11 provides a more detailed top-down view of the different geometric parameters used in this model. The following values are assumed for these parameters:

– d_{Offset} = 5 metres to 20 metres (y-axis offset distance from FS station to first lane in highway);

– w_{Lane} = 4 metres (width of each lane);

– w_{Car} = 2 metres (width of each car);

– $d_y = d_{Offset} + w_{Lane} \times (i_{Lane} - 0.5)$ (y-axis offset distance, in m, from automotive radar antenna to the FS);

- where i_{Lane} is the lane number of the road, starting with 1 being the lane closest to the FS station, and increasing by increments of 1;

– l_{Car} = 4 metres (length of each car);

– d_{Cars} = 10 metres to 50 metres (distance, in m, from front of one car to the front of the next car, with a uniform density of cars assumed);

– $n_{Cars/lane}$ = 10 to 500 (number of cars placed in front of each other by a distance d_{Cars}, within each single lane);

– l_x = −2 to 14 kilometres metres kilometres (x-axis offset distance between the front automotive radar antenna of the first column of cars and the FS station);

– $d_x = l_x + d_{Cars} \times (i_{column} - 1)$ (x-axis distance, in m, from front of the cars located in the i_{column}th column of cars, to the FS station);

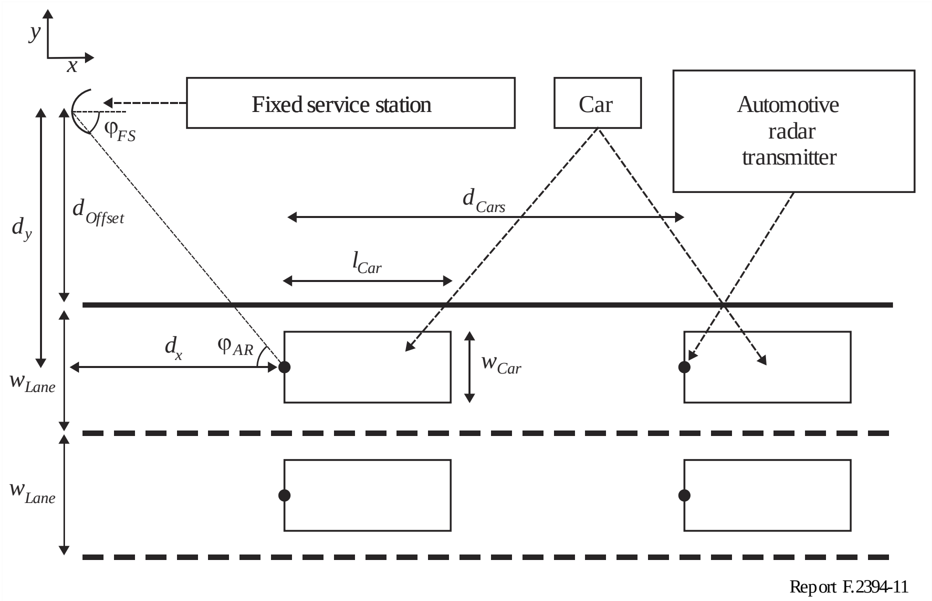
- where i_{column} is the column number of the car and is used to place adjacent cars in fixed increments d_{Cars} along the x-axis, starting with 1 being the column which is closest to the FS station when all the cars are in the positive x-axis, and increasing by increments of 1;

– $\varphi_{AR} = \tan^{-1}(d_y/d_x)$ (x-y plane azimuth angle, in degrees, from the main beam of the automotive radar antenna, to the FS antenna);

– $\varphi_{FS} = \varphi_{AR}$ (x-y plane azimuth angle, in degrees, from the main beam of the FS antenna to the automotive radar antenna).

FIGURE 11

Top-down view of geometric interference model



In Figs 11, 12 and 13, the placement of the radars in the front central part of the vehicle is for illustrative purposes. Clause 2.6.4 provides the precise details on the placement of the radars for each interference scenario considered in this report.

Figures 12 and 13 below provide a detailed side view of the remaining geometric parameters used in this model. The following values are assumed for these additional geometric parameters in this model:

– h_{AR} = 0.5 metres (height above ground where the automotive radar antenna is installed);

– h_{Car} = 1.5 metres (height of each car);

– h_{FS} = 3 metres to 20 metres (height of the FS station);

– $\theta_{AR} = \tan^{-1}((h_{FS} - h_{AR}) / d_x)$ (x-z plane elevation angle, in degrees, from the main beam of the automotive radar antenna, to the FS antenna);

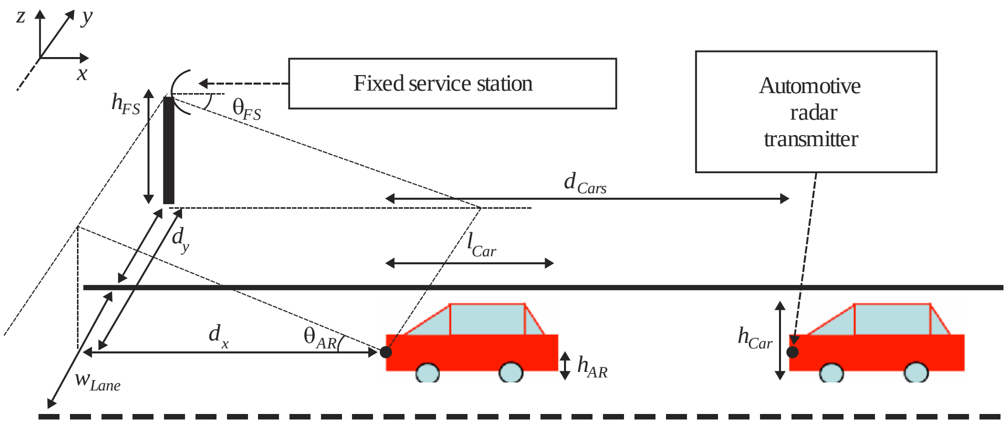
– $\theta_{FS} = \theta_{AR}$ (x-z plane elevation angle, in degrees, from the main beam of the FS antenna to the automotive radar antenna);

– α_{AR} (direct angle, in degrees, from the main beam of the automotive radar antenna, towards the immediate three-dimensional direction of the FS antenna;

– α_{FS} (direct angle, in degrees, from the main beam of the FS antenna, towards the immediate three-dimensional direction of the automotive radar antenna.

FIGURE 12

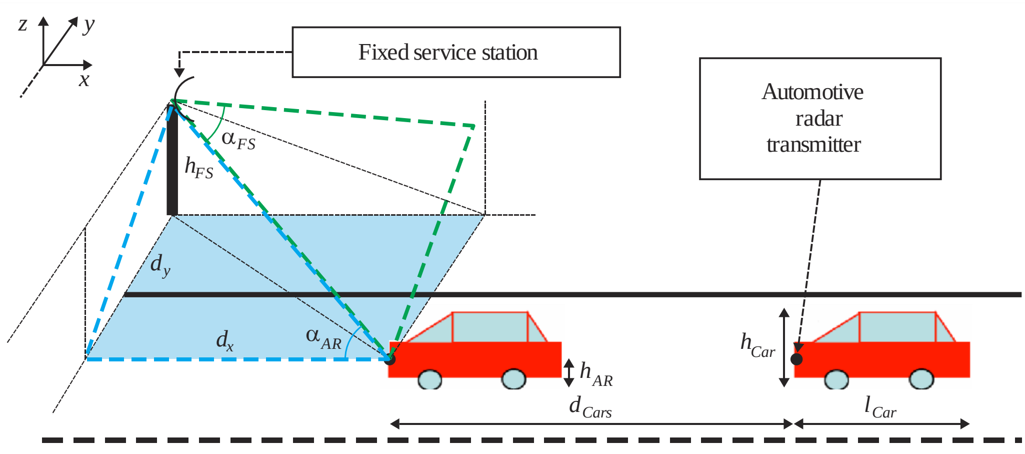
Sideways view of geometric interference model (showing elevation angles)



Report F.2394-12

FIGURE 13

Sideways view of geometric interference model (showing direct angles)



Report F.2394-13

Annex D

Detailed calculation results

The calculation results presented in §§ 4.1 and 4.2 are provided for specific combinations of parameters described in earlier sections of this study.

The graphical presentations given in this annex are made with $I/N = -20$ dB. The application of $I/N = -10$ will obviously move the zero ΔI reference up by 10 dB.

Calculation results are presented in the form of graphs where two parameters are varied while the other parameters are fixed to a specific value. The parameter plotted along the vertical axis is ΔI, which is the difference in the interference level received by the FS station and its maximum interference threshold. Positive values of ΔI indicate that the interference level exceeds the threshold value. The highest value of ΔI represents the maximum level of potential interference. The parameter plotted along the horizontal axis is l_x, the x-axis distance from the FS station to the LRR or SRR interferer(s). The x-axis value at which a line crosses the zero value of ΔI (y-Axis) represents the maximum distance at which the potential interference can occur. In the single LRR and SRR cases, it is the distance between the FS antenna and the vehicle. For the aggregate LRR and SRR cases, it is the distance between the FS station and the first column of cars, with each adjacent column located at a distance d_{cars} from the previous column.

D.1 Results for single entry interference

D.1.1 Results for automotive radars operating in the band 76-77 GHz (LRR)

Figure 14 summarizes the results of the interference calculations conducted for a single vehicle having a LRR and a FS station with varying antenna gains (G_{FS}) against antenna heights (h_{FS}), antenna elevation angles ($\theta_{FS,ant}$), and offset distances from the road (d_{offset}).

Figure 14a shows that the potential for interference exists when the automotive radar is pointed in the same direction as the azimuth of the FS antenna and located at distances between 0 kilometres and 7.5 to 9.5 kilometres. h_{FS} plays a major factor with the longest range for the highest height and the lowest range for the lowest height. Higher gain antenna only slightly reduces potential interference level ΔI due to its narrower beamwidth. In addition, at shorter distances, the maximum level of potential interference is independent of the FS antenna height and gain.

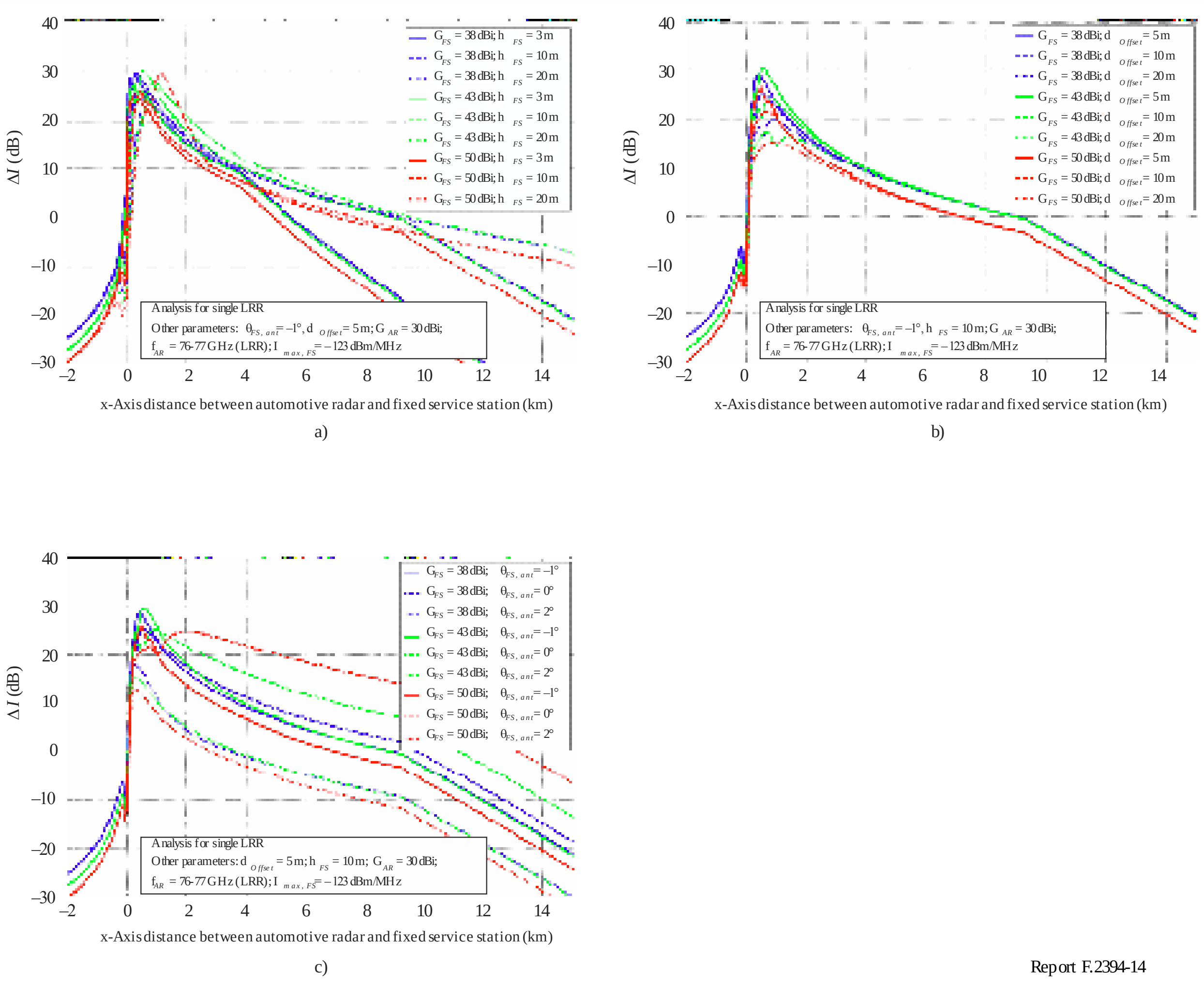
Figure 14b indicates that a larger offset distance for the FS station from the road decreases the potential for interference when the LRR is in close proximity, but has a negligible effect on the interference potential at larger distance. This is due to the greater discrimination angles provided by a larger offset distance when the LRR is in close proximity to the FS station.

Figure 14c indicates that the elevation angle of the FS station has a large impact on the range of distances where the interference potential exists (up to 13.1 km), with any angle differing from 0° reducing this range. A negative elevation angle increases the interference potential at short distances from the FS station (< 1 km), while a positive elevation angle decreases the interference potential at all distances. This is mainly due to the associated changes in FS discrimination angles as a direct result of changes in the antenna elevation angle.

Overall, in addition to reducing the level of potential interference by 10 dB, an I/N of −10 dB (instead of −20 dB) significantly reduces the maximum distance at which it can occur (10.5 km instead of 13.1).

FIGURE 14

Interference results for single LRR at different values of fixed station antenna gain, antenna height, antenna elevation angle, and offset distance from road



D.1.2 Results for automotive radars operating in the band 77-81 GHz (SRR)

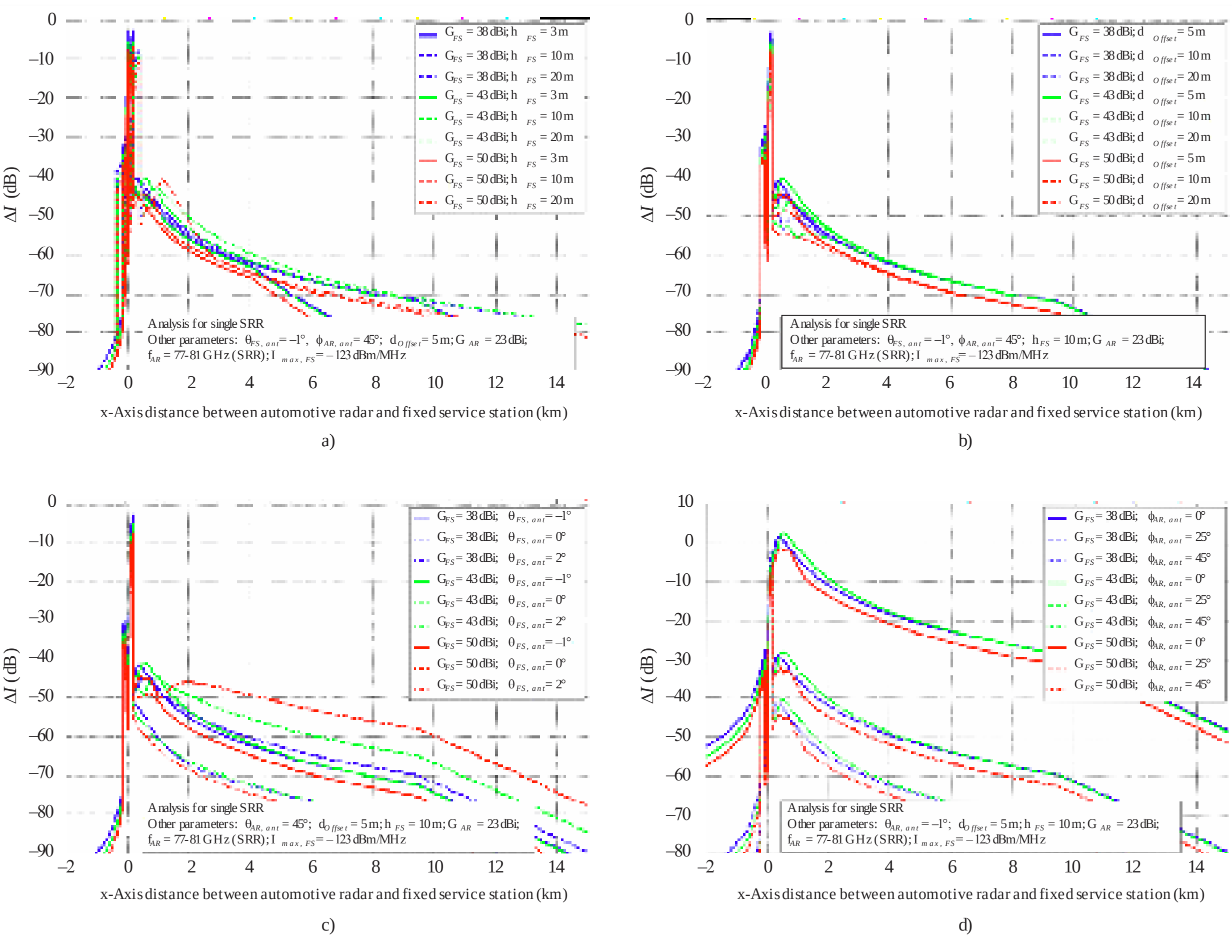
Calculations conducted for a single vehicle having SRRs (see Fig. 15 below) demonstrated the same general trends, discussed above, as those for LRR but with the ΔI level being lower by around 30 to 70 dB due to lower unwanted e.i.r.p. density (−30 dBm/MHz) of SRRs and the impact of the radar antenna azimuth angle ($\varphi_{AR,ant}$). The sharp increase just above 0 km occurs when the SRR antenna and FS antenna approach each other's main beam. This is due to the SRR antenna azimuth forming a 45° angle with the road axis.

Figure 15d shows the dramatic impact of the radar antenna azimuth angle. Any significant offset from 0° reduces the maximum interference level significantly due to the introduction of significant antenna discrimination factors and the absence of main-beam to main-beam coupling at larger positive distances. Although input received indicated that SRR radar would have an angle of 45° (see Fig. 8), a worst scenario of 0° has been added as the angle is expected to potentially vary from one deployment scenario to another.

Overall, these calculations indicate there is no potential for interference from a single vehicle's SRRs with either I/N of −10 and −20 dB, as long as $\varphi_{AR,ant}$ is 45°.

FIGURE 15

Interference results for SRR on a single vehicle at different values of fixed station antenna gain and antenna height, antenna elevation angle, offset distance from road, and radar antenna azimuth angle



Report F.2394-15

D.2 Results for aggregate interference

D.2.1 Results for automotive radars operating in the band 76-77 GHz (LRR)

Figures 16 and 17 summarize the results of the aggregate interference calculations for multiple vehicles having LRRs and a FS station with varying values of antenna gain (G_{FS}) against antenna height (h_{FS}), antenna elevation angle ($\theta_{FS,ant}$), offset distance from the road (d_{offset}), distance between cars (d_{cars}), number of cars per lane ($n_{cars/lane}$), and number of lanes of cars (n_{lanes}).

Figures 16a to 16c shows that for the aggregate interference case, an FS station with high h_{FS}, low d_{offset}, low $\theta_{FS,ant}$, and generally lower G_{FS} result in the highest ΔI at very short distances (< 1 km). This combination of parameters results in the FS station having a minimal amount of antenna discrimination towards a maximum amount of cars.

Figure 16d shows that a lower density of cars (i.e. higher d_{cars}) results in the worst case interference conditions. This is due to the reduced amount of LRRs having their interference path shielded by an adjacent vehicle.

Figure 17a shows that a larger n_{lanes} results in greater interference, with the effects more pronounced at high h_{FS}, due to reduced vehicular shielding across adjacent lanes.

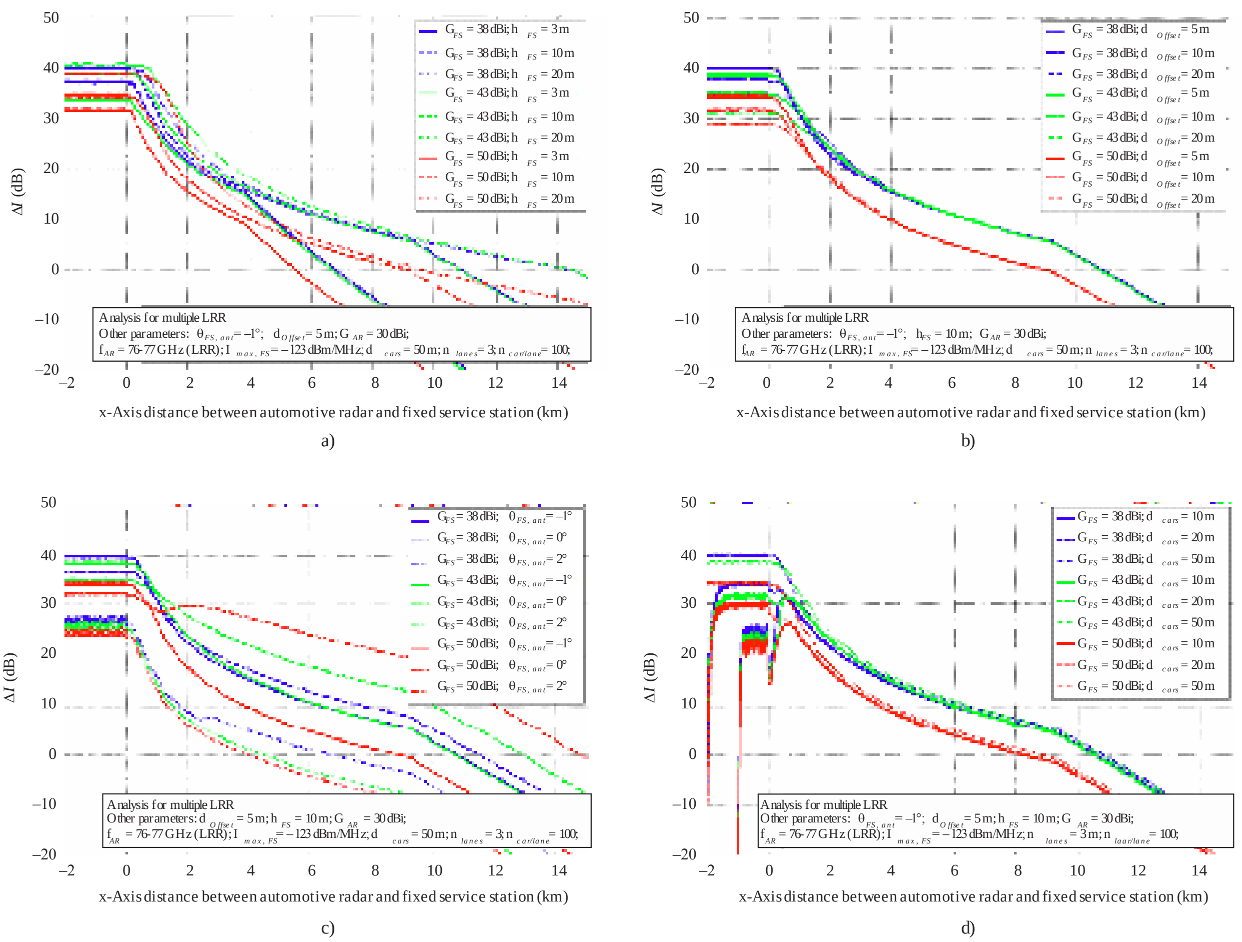
Figures 17b and 17c show that increasing the total number of interferers in a lane $n_{cars/lane}$ has only a small impact on the maximum ΔI, due to the fact that the main portion of the total interference is from a small amount of unshielded LRRs which are located close to the FS station. The highest interference level is for the highest h_{FS} and lowest d_{cars}. For a large $n_{cars/lane}$, ΔI flattens out to a maximum value in the negative portion of the x-axis because of the large number of trailing cars which remain in the positive x-axis and produce significant interference.

Similar to the single LRR case, in addition to reducing the level of potential interference by 10 dB, an I/N of −10 dB (instead of −20 dB) significantly reduces the maximum distance at which it can occur (12.1 km instead of 15).

The oscillations in interference levels seen in some parts of the figures for low h_{FS} values and short distances are presumed to be a numerical artefact caused by the calculation model switching between the different azimuth/elevation patterns to calculate the LRR antenna discrimination (see methodology described in § 2.2 above).

FIGURE 16

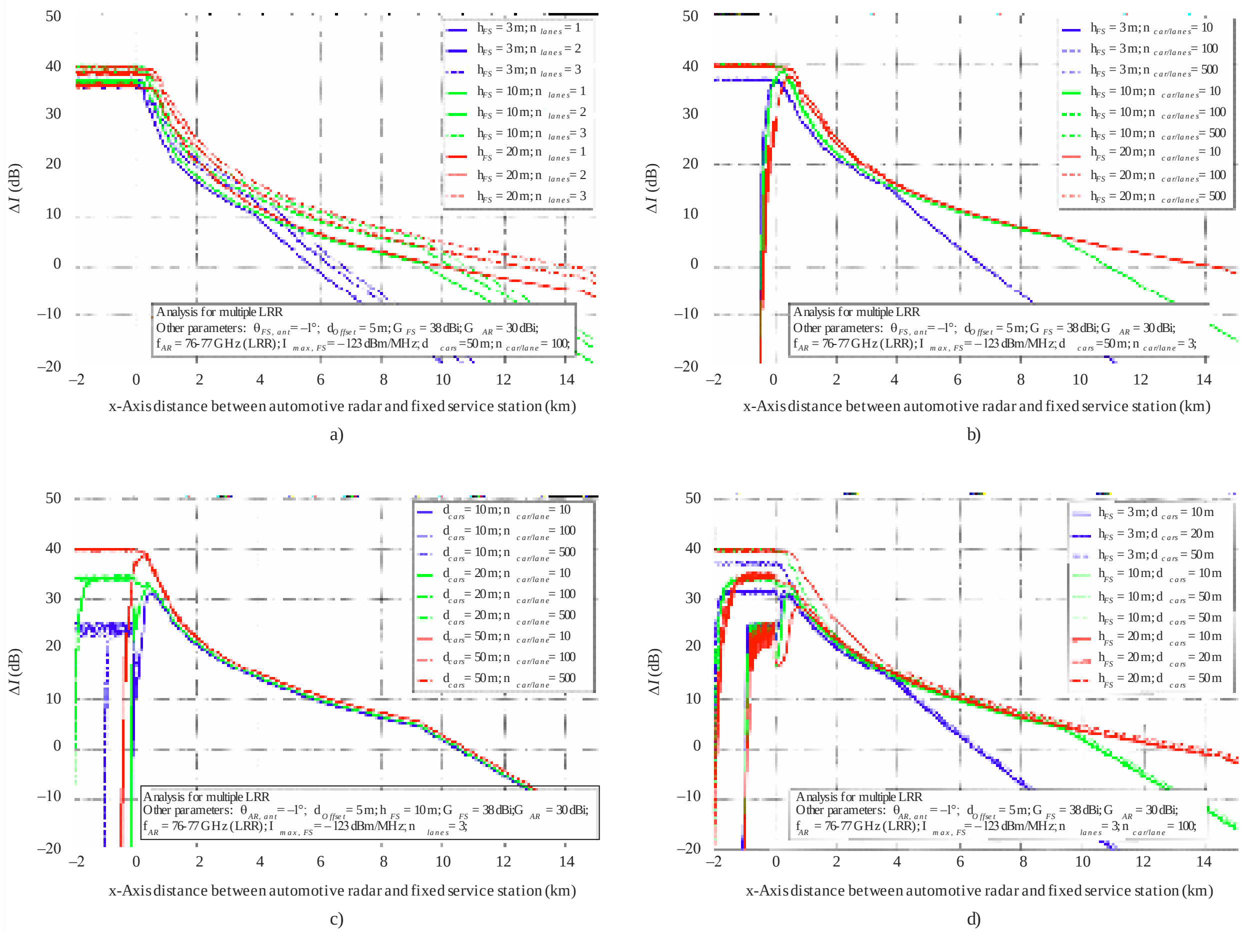
Interference results for LRR on multiple vehicles at different values of fixed station antenna gain, and antenna height, antenna elevation angle, offset distance from road, and distance between cars



Report F.2394-16

FIGURE 17

Interference results for LRR on multiple vehicles at different values of fixed station antenna height, distance between cars, number of lanes, and number of cars per lane



Report F.2394-17

D.2.2 Results for automotive radars operating in the band 77-81 GHz (SRR)

Figures 18 and 19 summarize the results of the aggregate interference calculations for multiple vehicles having SRRs and a FS station with varying values of antenna gain (G_{FS}) against antenna height (h_{FS}), antenna elevation angle ($\theta_{FS,ant}$), offset distance from the road (d_{offset}), distance between cars (d_{cars}), number of cars per lane ($n_{cars/lane}$), and number of lanes of cars (n_{lanes}). The effect of radar antenna azimuth angle is also considered ($\varphi_{AR,ant}$).

The aggregate interference calculations conducted using SRRs demonstrated some similar trends as those for LRRs but with the maximum Δ*I* level being lower by around 30 dB due to lower unwanted e.i.r.p. density (−30 dBm/MHz) of SRRs and the impact of the radar antenna azimuth angle ($\varphi_{AR,ant}$).

Similar to the LRR cases, in addition to reducing the level of potential interference by 10 dB, a *I*/*N* of −10 dB (instead of −20 dB) significantly reduces the maximum distance at which it can occur (12.1 km instead of 15).

Figures 18a to 18c demonstrate that similar to LRRs, the highest Δ*I* occurs for a FS station with higher h_{FS}, lower G_{FS}, lower d_{offset} and lower $\theta_{FS,ant}$. Additionally, Fig. 18d shows that a higher density of radars (i.e. low d_{cars}) at very short distance (< 1 km) produces the worst case interference, due to the lack of vehicular shielding on some of the SRRs placed in the first lane of cars which is closest to the FS station. In fact, none of the SRRs placed on the front-right of the vehicles in the first lane experience any shielding losses, regardless of d_{cars}. As a result, a higher density of radars results in a higher total interference level.

Figure 19a shows a larger n_{lanes} results in greater interference, as is also the case for LRRs.

Figures 19b and 19c show that increasing the total number of interferers in a lane $n_{cars/lane}$ has a significant impact on the maximum ΔI, again due to the lack of vehicular shielding in the first lane of cars. The highest interference level is for the highest h_{FS} and lowest d_{cars}.

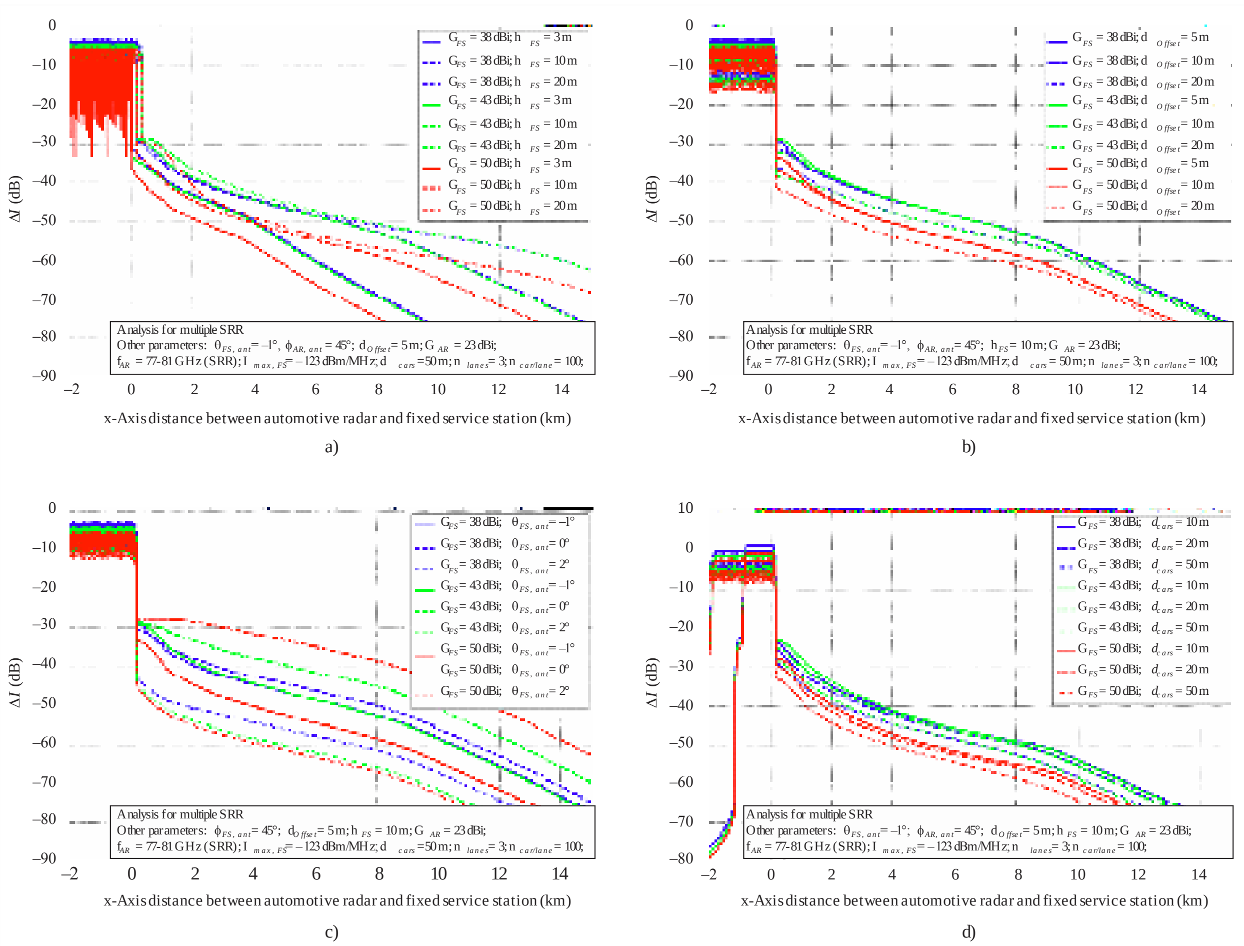
For a large $n_{cars/lane}$, ΔI flattens out to a maximum value in the negative portion of the x-axis, as is also the case for LRRs.

Also, quick variations of interference level in the negative distance values in Figs 18d and 19b to 19d are caused by the calculation process of considering multiple cars passing by the FS antenna. As long as many cars are still in the positive distance values, the potential for interference is high and then drops rapidly after the last cars have passed the FS station.

Finally, the oscillations in interference levels seen in the negative distances in some figures, as in the LRR cases, are presumed to be a result of the calculation model used in this study. The change in distance on the x-axis causes rapid variations in the antenna discrimination factors between the FS antenna and the set of cars remaining in the positive x-axis (since the additional vehicles are placed behind the first vehicle for which the distance value is shown in the x-axis) (see methodology described in § 2.2 above).

FIGURE 18

Interference results for SRR on multiple vehicles at different values of fixed station antenna gain, and antenna height, antenna elevation angle, offset distance from road, distance between cars, and radar antenna azimuth angle



Report F.2394-18

FIGURE 19

Interference results for SRR on multiple vehicles at different values of fixed station antenna height, distance between cars, number of lanes, number of cars per lane, and radar antenna azimuth angle