Sharing Between UWB Automotive Radars and FS Links at 24 GHz

Radiocommunications Agency

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1 INTRODUCTION

This report describes a study undertaken during June and July 2002 by Aegis Systems Limited for the Radiocommunications Agency into the feasibility of sharing between UWB automotive radars operating at 24 GHz and fixed links operating in the bands 22.0–23.6 GHz and 24.5–26.5 GHz.

The principal objectives of this study are to:

- establish representative FS link and UWB radar parameters
- develop a sharing analysis model
- design sharing scenarios
- apply the analysis model to the sharing scenarios.

This report commences with an outline of the UWB automotive radar and fixed service link sharing environment. The details of the representative system characteristics employed during the course of the study are then provided. This is followed by a description of the interference analysis and a presentation of the results. Finally, the key conclusions of the work are outlined.

2 BACKGROUND

Ultra Wide Band (UWB) as an emerging technology is a topic of live interest today. Proponents claim that it provides a great spectrum management opportunity, whereas regulators and existing spectrum users are concerned about its possible impact. The FCC has decided to allow vehicular radar systems to operate in the 24 GHz band. In Europe, a similar decision has not yet been made, although there have been a number of studies undertaken within CEPT and ETSI.

The use of automotive radar devices operating at or around 24 GHz is currently being promoted with a view to their deployment from 2003 onwards. The proposed short-range radars combine two functions:

- High resolution distance measurement providing speed information of an approaching object using Doppler radar. This is based on a narrowband signal (20 dBm peak / 0 dBm mean) falling within the short-range device band 24.05 to 24.25 GHz.
- A wide band radar providing the position of objects to a resolution of about 10 cm. This is based on a pseudo-noise coded signal spread across a band approximately ±2.5 GHz either side of the 24 GHz short-range device band.

It is intended that a number of these devices be placed along all sides of the vehicle in order to provide all round coverage. The proponents of this technology include 24 car and component manufacturers.

UWB automotive radar emissions will fall into the bands used by the Fixed Service, namely 22.0–23.6 GHz (the 23 GHz band) and 24.5–26.5 GHz (the 26 GHz band). These bands are used for low to high capacity (2 to 155 Mbps) digital point-to-point fixed links, often providing mobile system infrastructure.

The primary objective of this study is to determine the degree to which short-range radar devices might interfere with fixed links, assuming that the radar devices are likely to be deployed extensively.

3 SYSTEM CHARACTERISTICS

This section presents the key UWB automotive radar and fixed link parameters used in the interference analysis.

3.1 UWB Automotive Radar Characteristics

ETSI TR 101 982 is the technical report for 24 GHz automotive collision warning short-range radars. The document states that the mean and peak power limit of these radars are 0 and 20 dBm/1MHz, respectively, in the low power short-range device band 24.05–24.25 GHz. Outside the short-range device band, the radar average power spectral density is limited to -30 dBm/1MHz. Figure 1 illustrates the UWB radar transmitter mask.

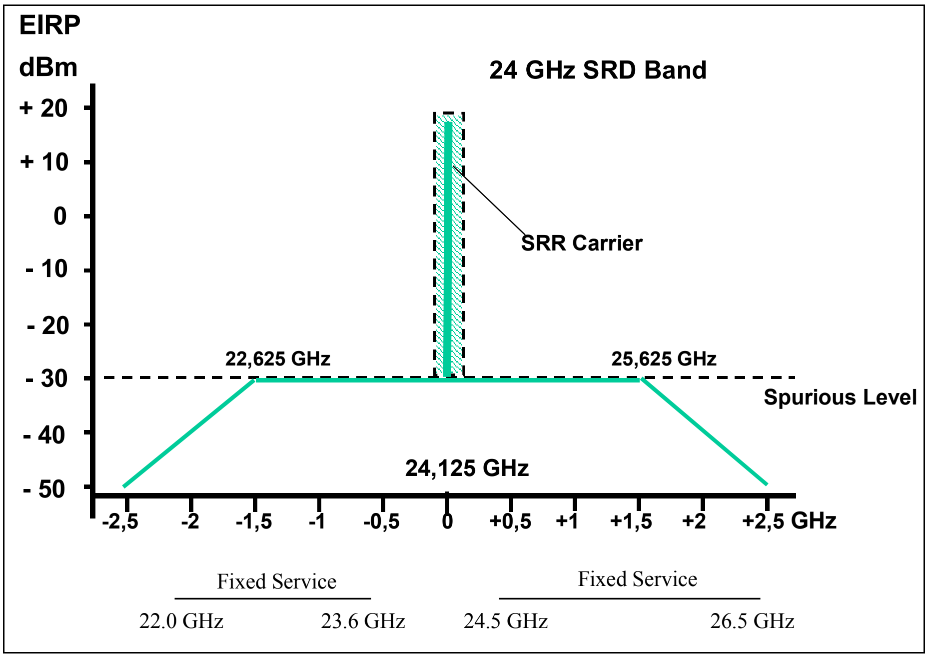

Figure 1: UWB Transmitter Mask

As can be seen, large parts of the FS allocations in the 23 and 26 GHz bands will be subject to UWB radar emissions at a level of -30 dBm/1MHz and the remaining parts of the allocations will be subject to emissions at less than this level. Consequently, this study has used a level of –30 dBm/1MHz in the calculations.

ETSI TR 101 982 also states that the average number of UWB radars per vehicle is expected to be in the range 4–8 and the percentage of cars using these devices is estimated to grow from 0.06% to 40% between 2003 and 2020. For the purposes of this study, penetration rates of up to 100% are taken into account during the modelling phase.

In addition to the above parameters, the analysis tool requires a radar height above the road level. In the modelling, this parameter is defined in relation to the total vehicle height and the vehicle base height (defined relative to the total vehicle height), which are variables. It is then assumed that radars operate at half of the vehicle base height. As an example, for a nominal total vehicle height of 1.4 m and a vehicle base height of 65% of the total vehicle height, the radars are modelled as operating at 0.45 m above the road, as shown in Figure 2.

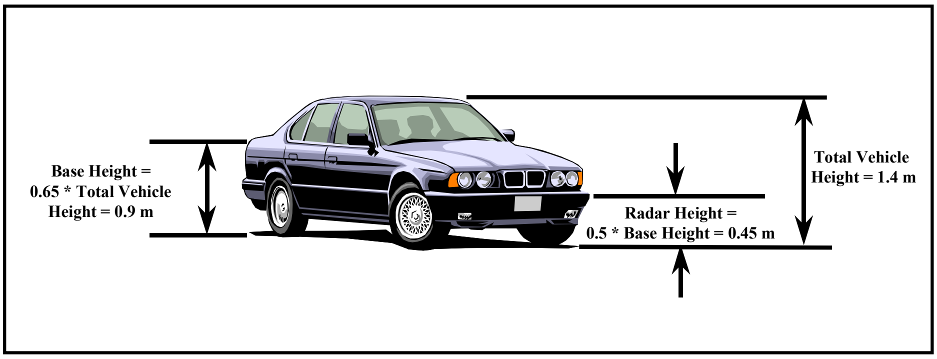

Figure 2: Radar Height

The following table summarises the UWB radar modelling parameters.

EIRP	-30 dBm/1MHz
No of Radars per Vehicle	1–8
Radar Penetration	up to 100%
Radar Height (a.g.l.)	½ of vehicle base height

Table 1: UWB Radar Parameters

3.2 Fixed Link Characteristics

It is noted that, in the UK, only point-to-point links are deployed in these bands, unlike some other European countries where point-to-multipoint systems are implemented.

The key FS link parameters for the modelling include the link length, the availability objective, the receiver noise figure, the channel bandwidth, the antenna pattern, the maximum antenna gain and the antenna height above ground level. In order to obtain generic results, sharing scenarios need to consider a range of values associated with these parameters.

FS system characteristics are defined in a number of documents. These include:

- ETSI standards EN 300 198 (23 GHz) and EN 300 431 (26 GHz), which define link parameter values

- the UK Radiocommunications Agency frequency assignment criteria documents RA 352 (23 GHz) and RA 348 (26 GHz)
- ITU-R Recommendation 758, which provides parameter values to be considered in sharing studies between FS and other services
- ETSI standard EN 300 833, which defines antenna patterns for the frequency band 3–60 GHz
- ITU-R Recommendation 699, which defines reference radiation patterns for fixed link antennas operating in the frequency range 1–70 GHz.

In addition to the above documents, real 23 and 26 GHz FS link characteristics provided by the UK Radiocommunications Agency were taken into account in deriving representative parameter values for the interference analysis. The locations and configuration of some of these links are illustrated in Figure 3 and Figure 4.

Figure 3: Example UK Links (23 GHz)

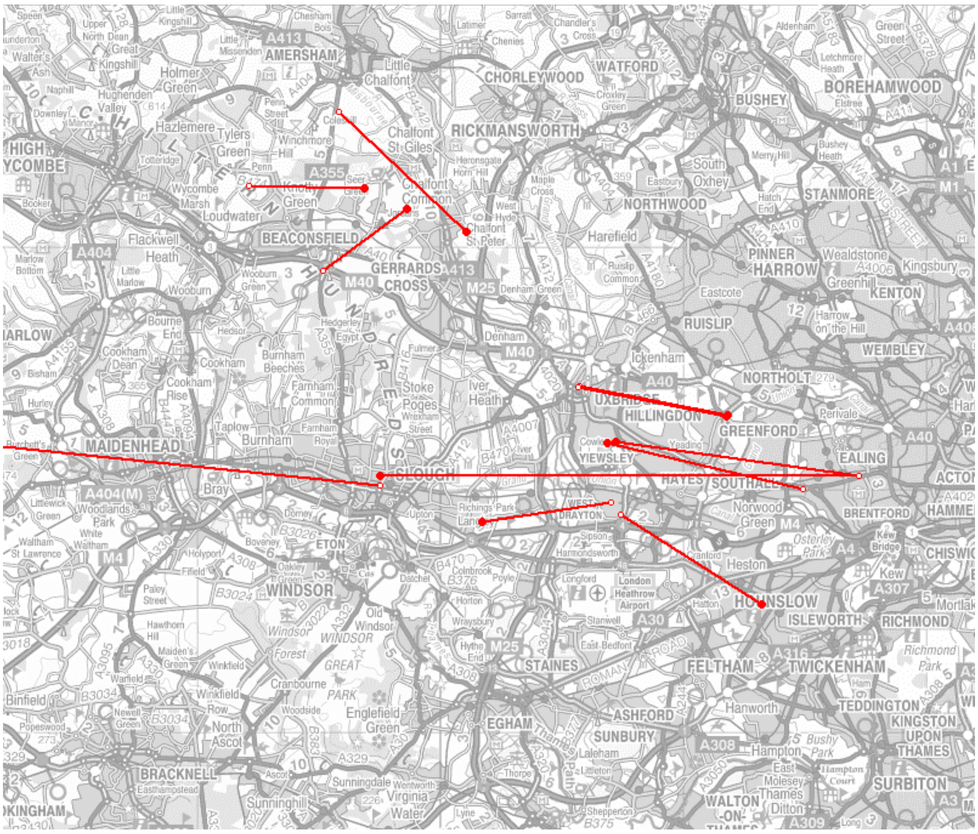

Figure 4: Example UK Links (26 GHz)

The above figures indicate that many FS links are aligned with busy roads and motorways and this should be taken into account in the modelling phase.

It is noted that the frequency assignment criteria documents RA 352 and RA 348 comply with ETSI standards EN 300 198 and EN 300 431, respectively. In RA 352 and 348, the minimum link length is defined to be 5 km except for the higher bit rate links (140/155 Mbps), which are allowed to operate over a distance of 2.5 km. Real link characteristics suggest that path lengths in the range 4–27 km exist for links operating in the 23 GHz band and 4–20 km for links operating in the 26 GHz band. The majority of these links have a path length less than 10 km.

The frequency assignment criteria documents also note that, in the 23 and 26 GHz bands, FS link design needs to consider rain fading effects. The nominal link availability requirement is specified to be 99.99%. It is also seen from the real link characteristics that the availability objective of approximately 80% of the links is 99.99% while the remaining vary between 99.97% and 99.999%.

The FS receiver noise figure is one of the key parameters used in examining the impact of UWB radar interference. The example link budgets given in the frequency assignment criteria documents suggest that the receiver noise figure is in the range 5–7 dB. In addition, Recommendation 758 specifies a noise figure value of 8 dB for the representative links defined for the 23 and 26 GHz bands.

As far as the FS link channel bandwidth values are concerned, the real link characteristics indicate that the bandwidth values are 3.5, 7, 14 and 28 MHz. The example link budgets in the frequency assignment criteria documents use the same bandwidths and an additional value of 56 MHz. It is noted that the bandwidths of the Recommendation 758 representative links are in the range 10–60 MHz.

As mentioned earlier, antenna radiation pattern envelopes for FS point-to-point links operating in the frequency range 3–60 GHz are provided in ETSI EN 300 833. In the frequency range 20–24 GHz, envelopes for radiation in the azimuth plane are defined for Class 1, 2 and 3 antennas. In the frequency range 24–30 GHz, azimuth envelopes are specified for Class 1 and 2 antennas.

The radiation envelopes are defined for off-axis angles over the range 5°–180°. In order to assess the implications of boresight or near boresight interference alignments, sharing scenarios require complete antenna patterns (i.e. defined over the range 0°–180°). Recommendation 699 provides a complete reference radiation pattern for fixed link antennas operating in the frequency range 1–70 GHz. For the purposes of this study, the ETSI antenna patterns are completed using Recommendation 699 for off-axis angles in the range 0°–5°.

ETSI EN 300 833 states that the minimum gain values are 28 dBi (for antennas requiring low gain for co-ordination purposes) and 32 dBi (for antennas requiring high gain for co-ordination purposes). Furthermore, the maximum antenna gain is specified to be 46 dBi in Recommendation 758. In addition, the example UK FS link characteristics suggest that actual maximum antenna gain values are in the range 35–49 dBi for the 23 GHz band links and 35–47 dBi for the 26 GHz band links.

As an illustration, Figure 5 shows complete antenna envelopes derived to model the FS receivers used in this study. In this figure, it is assumed that the maximum antenna gain is 40 dBi.

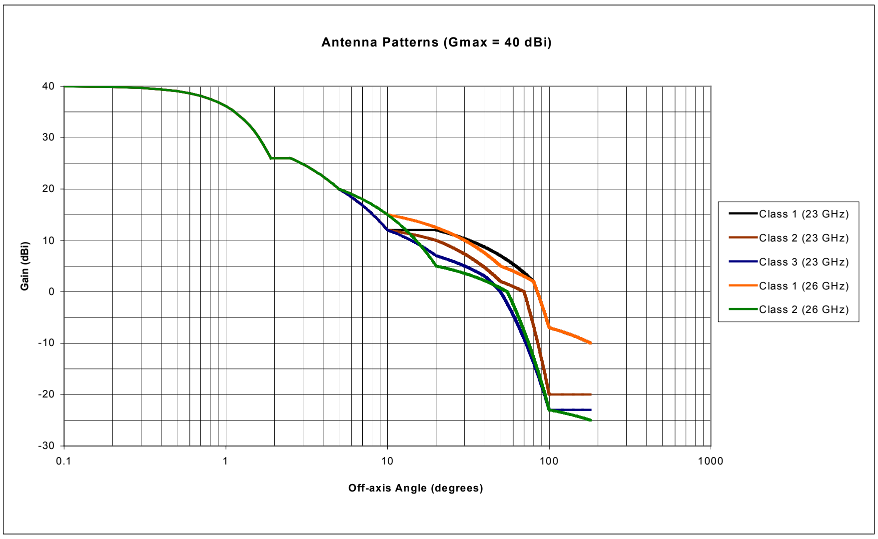

Figure 5: FS Receive Antenna Patterns

As stated earlier, these patterns are specified for the azimuth (horizontal) radiation plane. In the sharing analysis of UWB radars and FS links, the relationship between the radars and the fixed links needs to be considered in three dimensions which, in turn, implies that an assessment of the antenna gain in more than a single plane is required. For the purposes of this study and considering that the focus is on point-to-point links, it is assumed that the radiation patterns shown in Figure 5 are rotationally symmetrical (i.e. they can be used to model radiation in all planes).

In line with the above discussions, Table 2 summarises the FS link parameters used in the interference analysis.

Link Length	5–15 km
Availability Objective	99.99%
Noise Figure	5–8 dB
Channel Bandwidth	3.5–56 MHz
Maximum Antenna Gain	35–45 dBi
Antenna Height (a.g.l)	5–40 m

Table 2: FS Link Parameters

3.2.1 Interference Criteria

The impact of interference from UWB radars needs to be evaluated by taking FS link fading margins into account. In the frequency bands of concern, link margins are incorporated into the FS link budgets in order to overcome the fading due to rain and, thereby, satisfy the link availability objectives. For example, using the calculation methods defined in RA 352, it can be shown that a 12 dB fade margin is required to provide 99.99% availability for a link length of 5 km in the band 23 GHz.

Having determined the fade margin, consideration has to be given to the calculation of the portion of this margin that is taken up by interference from UWB radars. This is achieved by determining the relative increase in the receiver noise power due to the addition of interference to the receiver thermal noise:

$$\Delta N \text{ (dB)} = (10^*\log[N_{Thermal} \text{ (numeric)} + I \text{ (numeric)}]) - N_{Thermal} \text{ (dB)}$$

ΔN is then subtracted from the link margin. Fading statistics can then be used to determine the percentage of time for which the reduced link margin is exceeded. This percentage is compared against the link availability objective to determine the relative increase in unavailability due to interference.

As a final step, the calculated relative increase in the link unavailability percentage is compared against the maximum allowed unavailability increase of 1%, which is attributed to emissions from non-primary services sharing the band with the FS receivers (Recommendation ITU-R F.1094).

The application of the above-described method is described in detail in the following interference analysis section.

4 INTERFERENCE ANALYSIS

This section describes the interference modelling approach employed in this study. This is followed by a presentation of the results.

4.1 Approach

In order to gain an initial insight into the sharing potential between UWB radars and FS links, an analytical model was developed to explore single entry interference alignments, as illustrated in Figure 6.

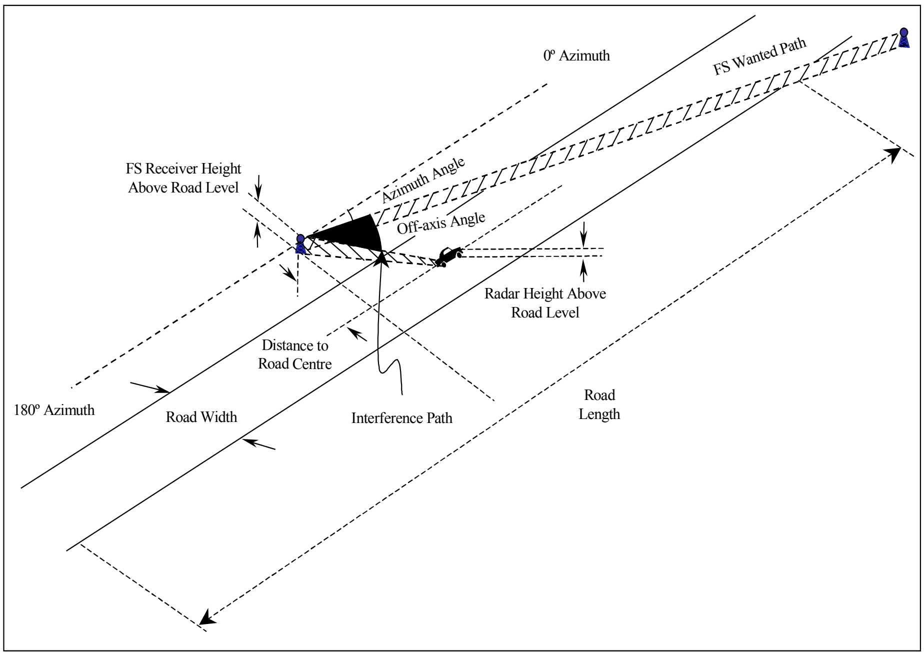

Figure 6: Single Interference Entry

As can be seen, the scenario is based on calculating interference at a fixed link receiver aligned along a road. In the analysis, taking the relative positions of the FS link plane and the interference path plane into account, the off-axis angle at the receiver is calculated. This angle is then used to determine the receive antenna off-axis gain which, together with the radar EIRP and the interference path loss (comprising free space propagation and atmospheric attenuation), allows the interference level to be calculated. The impact of single entry interference is examined by varying the relative positions of the FS link and the radar transmitter.

Taking the above approach as the baseline model, a simulation model was then developed to investigate the implications of interference aggregation from a population of vehicles in multiple lanes. The simulation model allows the user to configure different interference scenarios by specifying:

- the receiver distance from the centre of the road
- the receive antenna height above the road
- the link operating frequency, antenna pattern, bandwidth, maximum gain and pointing relative to the nearest lane

- the number of lanes, their length and width
- the vehicle shape (including van and car)
- the number of radars per vehicle and their location on the vehicle
- the separation distance between the vehicles
- the radar transmit power density
- the proportion of vehicles equipped with radar.

Having specified the above parameter values, interference is aggregated at the victim receiver. If all the vehicles are equipped with UWB radar transmitters then the result is a single aggregate interference. However, if only a proportion of the vehicles are equipped with radars then the simulation performs a number of Monte Carlo trials. In each trial, the road is populated with vehicles taking account of the separation distance specified by the user and the probability of a vehicle having radar equipment.

The aggregate interference model considers blockage from other vehicles. Using the relative receive antenna and radar transmitter positions, calculations are performed to determine if a line-of-sight path exists between each transmitter and the FS receiver. For line-of-sight paths (i.e. unblocked interference paths), interference is aggregated by applying free-space path loss and atmospheric attenuation. Interference analysis results are reported in the form of a cumulative distribution function specifying the probability of interference exceeding a given level.

4.2 Analysis

Initially, the impact of interference from a single transmitter is examined using the single entry analytic model described in the preceding section. This is followed by a simulation analysis where aggregate interference from multiple radar transmitters is investigated by employing the aggregate interference simulation model.

4.2.1 Single Entry Interference Analysis

Single entry interference analysis is implemented using the scenario shown in Figure 7. It is assumed that the FS receiver is operating at 23 GHz and the carrier bandwidth is 28 MHz.

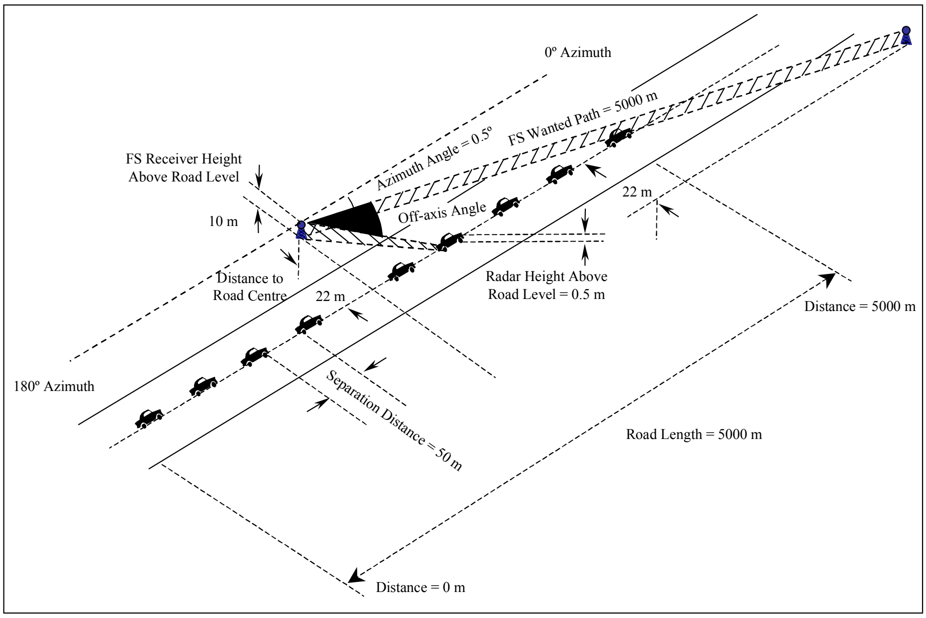

Figure 7: Single Entry Interference Geometry

As can be seen, the FS link is 5 km and antenna heights at both ends are 10 m above the road level. Furthermore, the road is 4 m wide and the UWB radar is assumed to be 0.5 m above the ground. Over a road section of 5 km, interference is calculated at each 50 m by considering the relative position of the UWB radar and the FS link in three dimensions.

For the 23 GHz antenna patterns illustrated in Figure 5, the single entry interference levels are plotted in Figure 8 as a function of distance (over the road section), assuming a maximum antenna gain of 40 dBi.

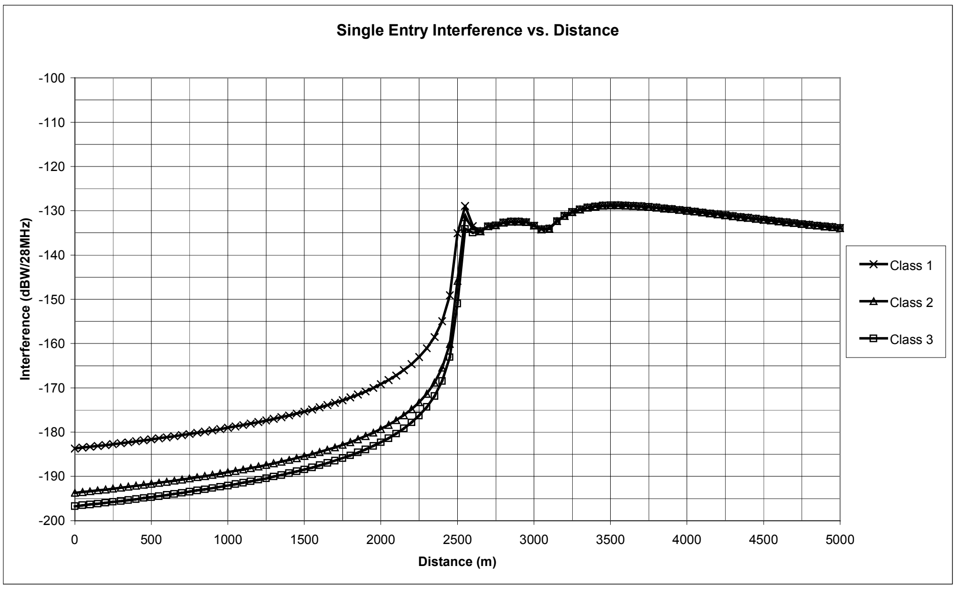

Figure 8: Single Entry Interference Levels

Interference levels are the same for all patterns when near on-beam interference entries are considered (i.e. when the off-axis angle at the receiver is ≤ 5°, corresponding to distances ≥ 2650 m from the beginning of the road), as the antenna radiation patterns are identical for these entries. The calculated interference levels differ for the far sidelobe entries, as the antenna patterns are not the same.

Assuming a noise figure of 8 dB, the FS receiver noise power is calculated to be -121.5 dBW/28 MHz. At the same time, the link is engineered for a maximum unavailability of 0.01% by providing a link margin of approximately 12 dB. The single entry analysis results indicate that the maximum interference level is approximately -128.5 dBW/28MHz. When this level of interference is present the receiver noise increases from -121.5 to -120.7 dBW/28 MHz (i.e. 0.8 dB of the 12 dB margin is taken up by interference). This, in turn, increases the unavailability from 0.01% to 0.012% as shown in Figure 9.

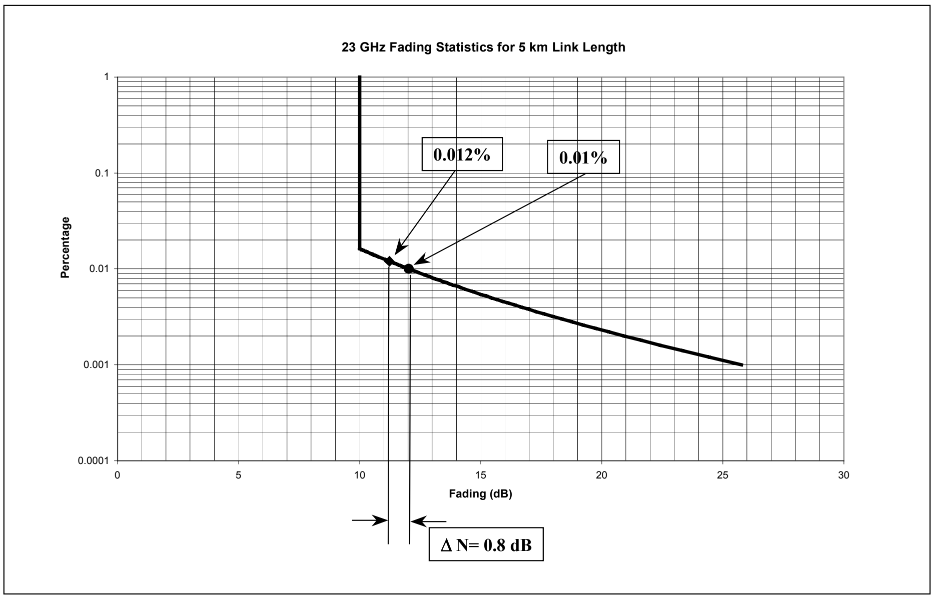

Figure 9: Impact of Maximum Single Entry Interference

It is worth noting that the 20% increase in the FS link unavailability due to a single UWB interference entry is well above the maximum allowed unavailability increase of 1% due to <u>all</u> emissions from non-primary services sharing the band with the FS receivers (Recommendation ITU-R F.1094).

4.2.2 Aggregate Interference Analysis

The aggregate interference simulator was configured to examine interference aggregation based on the scenario used in the single entry case. In this simple configuration, no vehicle shape is considered and each vehicle is modelled to be a point radar source located at 0.5 metre above the road level (i.e. there is no blocking). The distance between the consecutive radars is assumed to be 50 metres. The aggregate interference is then calculated to be:

- -114.03 dBW/28MHz at the Class 1 antenna
- -114.13 dBW/28MHz at the Class 2 antenna
- -114.18 dBW/28MHz at the Class 3 antenna.

For the purposes of verification, the single entry interference levels shown in Figure 8 were summed. It is noted that the results are the same as those obtained from the aggregate interference simulator.

For the assumed receiver thermal noise power level of -121.5 dBW/28 MHz (corresponding to an 8 dB noise figure), -114 dBW/28MHz aggregate interference results in an (N+I) of -113.3 dBW/28MHz which gives a ΔN of 8.2 dB. Considering that approximately 12 dB link margin is required to provide 99.99% availability (Figure 9), the UWB radar interference is taking up 2/3 of the link margin and will exceed the tolerable limits significantly.

It is worth re-iterating that the above scenario assumes that the FS receiver points diagonally across the road (i.e. the FS receive antenna azimuth is 0.5°) and that all transmitters are visible to the receiver. In order to examine the implications of a number of modelling parameters, sensitivity analysis needs to be carried out. The following sub-sections present the results of the sensitivity analysis.

4.2.2.1 Adjacent Vehicle Blocking in a Single Lane Road

Based on the preceding scenario (i.e. vehicles separated by 50 m in a single lane road interfering with an FS receiver at a 10 m height above the road level and pointing diagonally with respect to road, see Figure 7), the implications of blocking due to adjacent vehicles are examined by taking account of ‘car’ and ‘van’ vehicle shapes and different radar configurations.

Cars are modelled as 4 m long, 1.5 m wide and 1.4 m high. It is assumed that the base height is 65% of the vehicle height and the cabin is 60% of the vehicle length. The radars are assumed to be located at half the base height (i.e. 0.45 m above the ground level) on each car (see Figure 2). Vans are modelled as 4.5 m long, 1.5 m wide and 2 m high. The radars are assumed to be located at half of the height (i.e. 1 m above the road).

Four different radar configurations are considered. The first configuration assumes that each vehicle has one radar located in the middle of the front. In the second configuration, each vehicle is modelled to have two radars, one located in the middle of the front and one located in the middle of the back. The third configuration assumes that each vehicle has four radars, one located in the middle of each side. The fourth configuration comprises eight radars per vehicle – there are two radars on each side and the distance between them is 1/3 of the vehicle length/width.

The simulator was used to calculate aggregate interference levels corresponding to a number of scenarios based on the use of cars and vans with different radar configurations. As the road length is assumed to be 5,000 m and the vehicle separation is 50 m, there are 101 vehicles in each scenario. Therefore, the total number of radar transmitters is 101, 202, 404 and 808, corresponding to the radar configurations of one, two, four and eight per vehicle. Due to adjacent car blocking, only a portion of these transmitters will be visible to the victim receiver.

In the analysis, all vehicles are assumed to have radars (i.e. the radar penetration is 100%). Interference is then aggregated at the FS receiver (assumed to be operating at 23 GHz with a bandwidth of 28 MHz) for Class 1, 2 and 3 antenna patterns defined in Section 3.2. Results are summarised in Table 3.

Scenario	***Total Number of Visible Radars***	***Aggregate Interference (dBW/28MHz)***		
		Class 1	***Class 2***	***Class 3***
Car -1 radar	27 of 101	-146.77	-157.53	-160.53
Car -2 radars	54 of 202	-116.31	-116.43	-116.51
Car -4 radars	155 of 404	-111.81	-111.91	-111.97
Car -8 radars	322 of 808	-108.72	-108.82	-108.88
Van -1 radar	26 of 101	-146.74	-157.49	-160.49
Van -2 radars	52 of 202	-116.39	-116.52	-116.61
Van -4 radars	153 of 404	-111.78	-111.89	-111.95
Van -8 radars	320 of 808	-108.64	-108.75	-108.80

Table 3: Aggregate Interference

Table 3 suggests that:

- For the assumed 50 m vehicle separation, differences in blocking due to the vehicle shape are not significant – the number of visible radars is almost the same for the scenarios employing cars and vans. For example, the differences in the aggregate interference levels for the scenarios with two radars per car and two radars per van are less than 0.1 dB. The same is true for the 'one radar per vehicle', 'four radars per vehicle' and 'eight radars per vehicle' scenarios.
- In the single radar per car (van) scenario, 26.7% (25.7%) of the transmitters are visible to the receiver. These transmitters are those located on vehicles approaching the receiver. When a vehicle passes the FS receiver, the vehicle itself will block a front-mounted transmitter. Since the receiver is pointing diagonally ahead of the vehicle (see Figure 7), interference from vehicles approaching the receiver comes through the far side lobes of the receive antenna. Aggregate interference levels (which are in the range -160.53 to -146.74 dBW/28MHz) are therefore much lower than those calculated for other scenarios. For a given vehicle shape, there are small differences in the aggregate interference levels due to the differences in the far side lobes of the Class 1, 2 and 3 antennas.
- In the two radars per car (van) scenario, 26.7% (25.7%) of the transmitters are visible to the receiver – which is the same as before. However, the total number of transmitters is doubled (see Table 3). As there are radars at the front and back of each vehicle, the interference geometry will be symmetrical with respect to the FS receiver location. Therefore, there will be twice as many transmitters visible to the FS receiver as compared to the previous scenario. The aggregate interference values (which are calculated to be between -116.61 dBW/28MHz and -116.31 dBW/28MHz) indicate that interference paths from rear-mounted

radars include near on-beam entries that dominate the interference – the interference has increased by 30 dB or more, which is much larger than the 3 dB attributable to the doubling of the number of transmitters. For a given vehicle shape, the aggregate interference levels are very close to each other as the boresight and first side lobe patterns are the same for all antenna patterns.

- In the four radar per car (van) scenario, 38.4% (37.9%) of the transmitters are visible to the receiver. As the road is assumed to be a single lane, the radar located at the side nearest to the FS receiver is visible for all vehicles. In addition, for vehicles approaching the receiver, radars located at the front of some of the vehicles are also visible to the receiver, depending on blocking. The same argument applies when vehicles are ahead of the FS receiver. In this case, radars located at the back of some of the vehicles are visible to the receiver. The aggregate interference level calculated for all 'four radars per vehicle' scenarios is approximately -112 dBW/28MHz, which includes the aggregation of a number of near on-beam interference entries. As in the two radars per vehicle scenario, for a given vehicle shape, the aggregate interference levels are very close to each other as the boresight and near side lobe patterns are the same for all antenna patterns.
- In the eight radar per car (van) scenario, 39.9% (39.6%) of the transmitters are visible to the receiver. For each vehicle, the interference paths from the two radars located on the side nearest the FS receiver are line-of-sight. As in the 'four radar per vehicle' case, there is an interference contribution from the radars at the front and back of some of vehicles that are approaching or have just passed the FS receiver. The aggregate interference level calculated for all 'eight radar per vehicle' scenario is approximately -109 dBW/28MHz, which is 3 dB higher than the interference level calculated for the 'four radars per vehicle' scenario.

For a number of FS link lengths and receiver noise figures, the implications of the above-calculated maximum aggregate interference levels are examined by calculating the increase in the link unavailability. Tables 4–7 show the calculation process for the 'one radar per vehicle', 'two radars per vehicle', 'four radars per vehicle' and 'eight radars per vehicle' scenarios.

Scenario : 'One Radar per Vehicle'				
Maximum Interference (I) (dBW/28 MHz)		-146.74		
Thermal Noise Power (N) (dBW/28 MHz)	*NF = 5 dB*	-124.5		
	NF = 6.5 dB	-123		
	NF = 8 dB	-121.5		
N+I (dBW/28 MHz)	*NF = 5 dB*	-124.47		
	NF = 6.5 dB	-122.98		
	NF = 8 dB	-121.49		
ΔN = (N+I) - (N) (dB)	*NF = 5 dB*	0.03		
	NF = 6.5 dB	0.02		
	NF = 8 dB	0.01		
FS Link Length (km)		5	10	15
Margin for 99.99% Availability (dB)		12.027	20.447	26.671
Margin - ΔN (dB)	*NF = 5 dB*	11.997	20.417	26.641
	NF = 6.5 dB	12.007	20.427	26.651
	NF = 8 dB	12.017	20.437	26.661
Percentage of time Margin – ΔN is exceeded	*NF = 5 dB*	0.010066	0.010039	0.010030
	NF = 6.5 dB	0.010045	0.010026	0.010020
	NF = 8 dB	0.010022	0.010013	0.010010
Unavailability Increase due to ΔN	*NF = 5 dB*	0.66%	0.39%	0.3%
	NF = 6.5 dB	0.45%	0.26%	0.2%
	NF = 8 dB	0.22%	0.13%	0.1%

Table 4: Implications of Aggregate Interference - 'One Radar per Vehicle'

Scenario : 'Two Radars per Vehicle'				
Maximum Interference (I) (dBW/28 MHz)		-116.31		
Thermal Noise Power (N) (dBW/28 MHz)	*NF = 5 dB*	-124.5		
	NF = 6.5 dB	-123		
	NF = 8 dB	-121.5		
N+I (dBW/28 MHz)	*NF = 5 dB*	-115.70		
	NF = 6.5 dB	-115.47		
	NF = 8 dB	-115.16		
ΔN = (N+I) - (N) (dB)	*NF = 5 dB*	8.8		
	NF = 6.5 dB	7.53		
	NF = 8 dB	6.34		
FS Link Length (km)		5	10	15
Margin for 99.99% Availability (dB)		12.027	20.447	26.671
Margin - ΔN (dB)	*NF = 5 dB*	3.227	11.647	17.871
	NF = 6.5 dB	4.497	12.917	19.141
	NF = 8 dB	5.687	14.107	20.331
Percentage of time Margin – ΔN is exceeded	*NF = 5 dB*	>0.0162	0.0408	0.0277
	NF = 6.5 dB	>0.0162	0.0319	0.0234
	NF = 8 dB	>0.0162	0.0258	0.0202
Unavailability Increase due to ΔN	*NF = 5 dB*	>62%	308%	177%
	NF = 6.5 dB	>62%	219%	134%
	NF = 8 dB	>62%	158%	102%

Table 5: Implications of Aggregate Interference - 'Two Radars per Vehicle'

Scenario : 'Four Radars per Vehicle'				
Maximum Interference (I) (dBW/28 MHz)		-111.78		
Thermal Noise Power (N) (dBW/28 MHz)	*NF = 5 dB*	-124.5		
	NF = 6.5 dB	-123		
	NF = 8 dB	-121.5		
N+I (dBW/28 MHz)	*NF = 5 dB*	-111.55		
	NF = 6.5 dB	-111.46		
	NF = 8 dB	-111.34		
ΔN = (N+I) - (N) (dB)	*NF = 5 dB*	12.95		
	NF = 6.5 dB	11.54		
	NF = 8 dB	10.16		
FS Link Length (km)		5	10	15
Margin for 99.99% Availability (dB)		12.027	20.447	26.671
Margin - ΔN (dB)	*NF = 5 dB*	-0.923	7.497	13.721
	NF = 6.5 dB	0.487	8.907	15.131
	NF = 8 dB	1.867	10.287	16.511
Percentage of time Margin – ΔN is exceeded	*NF = 5 dB*	>0.0162	>0.0582	0.0517
	NF = 6.5 dB	>0.0162	>0.0582	0.0412
	NF = 8 dB	>0.0162	0.0544	0.0335
Unavailability Increase due to ΔN	*NF = 5 dB*	>62%	>482%	417%
	NF = 6.5 dB	>62%	>482%	312%
	NF = 8 dB	>62%	444%	235%

Table 6: Implications of Aggregate Interference - 'Four Radars per Vehicle'

Scenario : 'Eight Radars per Vehicle'				
Maximum Interference (I) (dBW/28 MHz)		-108.64		
Thermal Noise Power (N) (dBW/28 MHz)	*NF = 5 dB*	-124.5		
	NF = 6.5 dB	-123		
	NF = 8 dB	-121.5		
N+I (dBW/28 MHz)	*NF = 5 dB*	-108.53		
	NF = 6.5 dB	-108.48		
	NF = 8 dB	-108.42		
ΔN = (N+I) - (N) (dB)	*NF = 5 dB*	15.97		
	NF = 6.5 dB	14.52		
	NF = 8 dB	13.08		
FS Link Length (km)		5	10	15
Margin for 99.99% Availability (dB)		12.027	20.447	26.671
Margin - ΔN (dB)	*NF = 5 dB*	-3.943	4.477	10.701
	NF = 6.5 dB	-2.493	5.927	12.151
	NF = 8 dB	-1.053	7.367	13.591
Percentage of time Margin – ΔN is exceeded	*NF = 5 dB*	>0.0162	>0.0582	0.0903
	NF = 6.5 dB	>0.0162	>0.0582	0.0681
	NF = 8 dB	>0.0162	>0.0582	0.0528
Unavailability Increase due to ΔN	*NF = 5 dB*	>62%	>482%	803%
	NF = 6.5 dB	>62%	>482%	581%
	NF = 8 dB	>62%	>482%	428%

Table 7: Implications of Aggregate Interference - 'Eight Radars per Vehicle'

Tables 4–7 indicate that:

- For the 'one radar per vehicle scenario', the degradation caused by the maximum UWB interference is within tolerable limits. It is worth remembering that in this scenario, interference entries are through the far side lobes of the FS link receive antenna. For comparison, the one radar per car scenario was re-simulated by assuming that the FS receiver is pointing towards the approaching cars, rather than away from them (i.e. the FS receiver azimuth is 179.5°). In this case, the aggregate interference value at the Class 1 antenna is calculated to be -116.33 dBW/28MHz, which is approximately 30 dB higher than the aggregate interference level calculated for the scenario where the receiver azimuth angle is assumed to be 0.5° (see Figure 7). This result suggests that when the receive antenna pointing is 179.5° the interference is dominated by near on-beam interference paths.
- For the multiple radar per vehicle scenarios, where there are near on-beam interference entries, FS links are severely degraded. In all cases, the interference criterion is exceeded by a significant margin. The UK RA frequency assignment criteria documents state that the minimum FS link margin in the 23 GHz and 26 GHz bands is 10 dB. Therefore, when '*Margin- ΔN*' is below 10 dB the maximum percentage of time for which the margin is less than or equal to 10 dB is shown in Table 5, 6 and 7 for '*percentage of time Margin - ΔN is exceeded*' (see Figure 9).

It is worth re-stating that the above interference scenarios are based on the assumption of 101 vehicles aligned in a single lane road, all employing UWB automotive radars. The following section examines the implications of aggregate interference for a range of FS receive antenna azimuths from multiple lane roads. In the remainder of this report, all interference scenarios take account of blocking due to other vehicles.

4.2.2.2 Interference Aggregation from Multiple Lanes

Calculations presented in this section examine the implications of vehicle blocking in a multiple-lane environment. Aggregate interference powers from 4-radar cars separated by a 50 m distance are derived assuming that the road modelled comprises multiple lanes. It is also assumed that the FS receiver operates at 23 GHz, the receiver bandwidth is 28 MHz and the antenna pattern is Class 2. Furthermore, the maximum receive antenna gain is assumed to be 40 dBi.

Initially, using a 4-lane road, the impact of the FS receive antenna pointing is examined by varying the azimuth angle from 0° to 360° at a step size of 5°. Figure 10 illustrates the interference scenario.

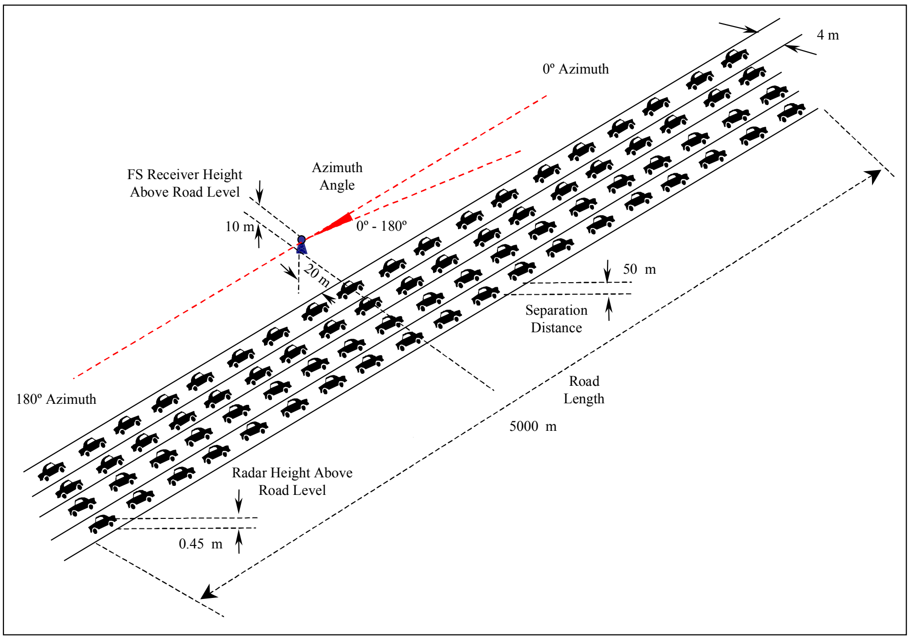

Figure 10: Four Lane Interference Scenario (four radars per car)

As the road length is 5,000 m and the cars are separated by 50 m, there are 404 cars, each with four radars. At each azimuth, 562 of the 1616 radar transmitters are calculated to be visible due to blocking resulting from adjacent cars. Interference is then aggregated by applying free-space path loss and atmospheric attenuation models to each line-of-sight interference path. Figure 11 illustrates the aggregate interference as a function of the receiver azimuth angle.

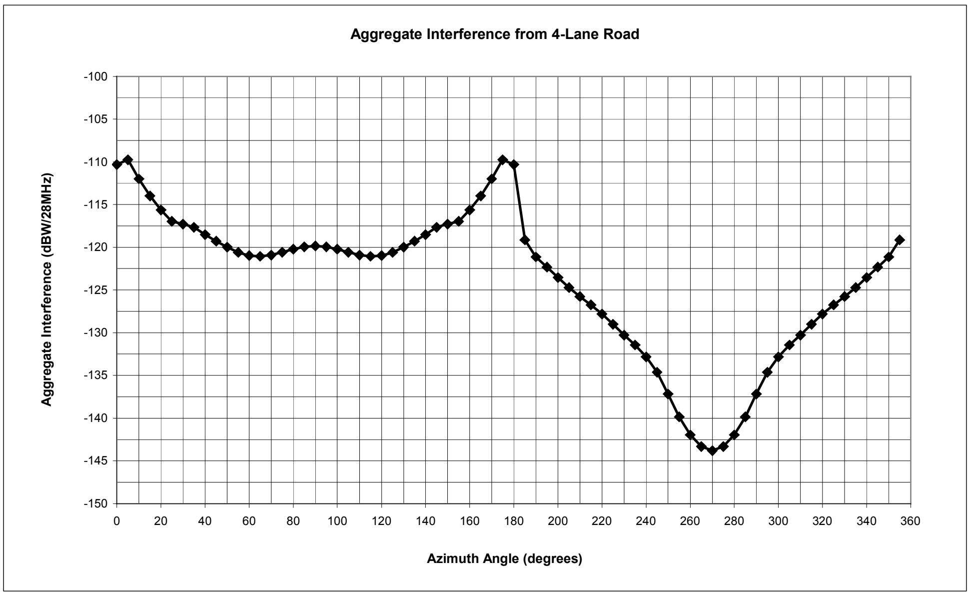

Figure 11: Aggregate Interference vs Azimuth Angle

The aggregate interference plot shows that interference is at a maximum when the FS receiver is pointing diagonally (at an azimuth of 5°) with respect to the 4-lane road populated with 4-radar cars spaced at 50 metres. Interference is a minimum when the azimuth is 270°, as expected.

It can be shown that, for an assumed FS link length of 10 km and the receiver noise figure level of 6.5 dB, the maximum calculated interference level (-109.76 dBW/28MHz) takes up 13.44 dB of the total link margin of 20.45 dB, which results in an unacceptable increase in the link unavailability (>482%).

As a next step, the effect of an increase in the number of lanes is examined by assuming that the road has six lanes. In this case, the road is populated with 606 vehicles. Among 2424 radar transmitters, 714 are calculated to be visible to the FS receiver. At the FS receiver azimuth angle of 5°, aggregate interference is calculated to be -108.14 dBW/28MHz. This indicates that a 50% increase in the number of lanes results in an increase of 1.62 dB in the aggregate interference.

So far, interference scenarios have been based on the application of a deterministic approach. In other words, for a set of user specified parameter values, the simulator is used to populate a road with vehicles and calculate the aggregate interference from UWB radar transmitters located at each vehicle. In the following section, the implications of radar penetration rate are investigated using a Monte Carlo method.

4.2.2.3 Radar Penetration Rate

ETSI TR 101 982 states that the percentage of cars using UWB radars is estimated to reach 40% by 2020. In this section, the impact of the radar penetration is examined for a number of assumed rates. For this analysis, the simulator is configured to implement Monte Carlo simulations, since a relatively small number of near on-beam entries may dominate interference levels.

In each Monte Carlo trial, the distance between the start (or end) of the road and the first car in each lane is selected randomly (up to the separation distance). The other cars are then equally spaced relative to the first car. This approach ensures that the relative positions of cars are different in consecutive trials. In the runs, the probability of a car being equipped with UWB radars is determined from the radar penetration rate. Simulations are implemented over a user defined total number of trials and the results are reported in the form of a cumulative distribution function defining the probability of aggregate interference exceeding a given level. Interference values are stored in 1 dB bins (for example, any interference level between -125.5 and -124.4 is stored as -125).

The simulation scenario is the same as that used in the preceding section when examining interference aggregation from a 4-lane road. It is assumed that the FS receiver azimuth angle is 5° with respect to the direction of travel in the nearest lane, representing the worst-case alignment. The radar penetration rates are taken to be 1, 5, 10, 20, 40, 50, 75 and 100%. For each penetration level, a total of 1,000 trials were carried out. Figure 12 illustrates the interference statistics obtained from these trials. For an assumed noise figure of 6.5 dB, the FS receiver thermal noise power is also included in the following figure. It should be noted that the criterion corresponding to a 1% increase in outage is approximately 20 dB below the receiver thermal noise power.

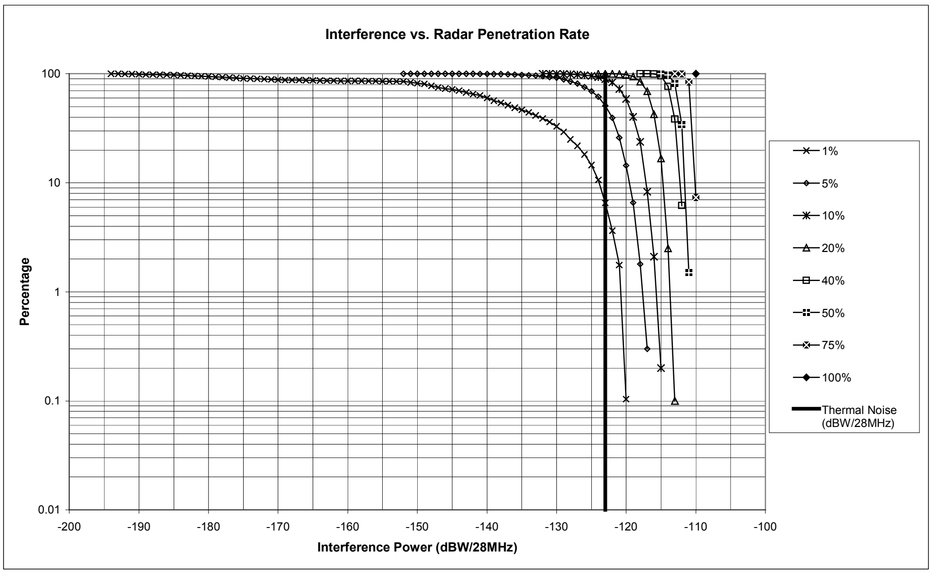

Figure 12: Aggregate Interference vs UWB Radar Penetration Rate

The interference statistics show that the receiver noise floor is exceeded for all penetration rates. In particular, the probability of exceeding the noise floor is greater than approximately 90% for penetration rates higher than 10%. It is worth noting that when the aggregate interference level is equal to the FS receiver noise power, 3 dB of the available margin is taken up by the interference. Assuming that the FS link is 10 km and the availability requirement is 99.99%, it can be shown that the remaining margin is 17.45 dB. Using 10 km link fading statistics, the percentage of time for which the margin of 17.45 dB is exceeded is calculated to be 0.015%. This translates to a 50% increase in the receiver unavailability. Clearly, this level of increase is far above the 1% criterion.

The results also suggest that, for a given exceedence probability, an increase in the radar penetration results in higher aggregate interference. This is more significant at lower penetration rates (i.e. <40%). For example, the probability of aggregate interference being greater than -124 dBW/28MHz is 10% for a penetration rate of 1%. For the same probability, the interference level increases by 5 dB when the penetration rate is increased to 10%. On the other hand, the increase is limited to 1 dB when the penetration rate is increased from 50% to 75%.

It is worth noting that when the penetration rate is 100%, the variation in the aggregate interference statistics is only due to the random selection (in each trial) of the distance between the start (or end) of each lane and the first car positioned in that lane. This also determines the positions of all remaining cars as they are used to populate the lanes according to the fixed separation distance. The detailed simulation results suggest that the random selection of the position of the first car results in a total number of visible transmitters varying between 559 and 573 (out of a total of 1616) due to different geometries leading to different car blocking in each trial. This, in turn, leads to aggregate interference levels between -110.196 and -109.605 dBW/28MHz. As interference levels are stored in 1 dB wide bins, for the 100% penetration rate, the probability of aggregate interference exceeding -110 dBW/28 MHz is 100% (i.e. the cdf corresponding to a 100% penetration rate is represented by a single point in Figure 12).

The preceding interference scenarios are based on the assumption of vehicles populating single and multiple lanes over a road length of 5,000 m. The effects of varying the road length are investigated in the next section.

4.2.2.4 Road Length

On the basis of the 4-lane interference scenario shown in Figure 10, road lengths of 2, 5, 10 and 15 km were simulated for an assumed vehicle separation of 50 m. For each road length, the FS receiver is centred on the road section, 28 m from the road centre. The vehicles use four radars (one on each side) and the penetration rate is 40% (which is an estimated value for the year 2020). As before, the FS receive antenna azimuth is taken to be 5° (with a 40 dBi maximum gain) and the antenna radiation pattern is assumed to be Class 2. Interference statistics shown in Figure 13 are based on 1,000 Monte Carlo trials. For comparison, the receiver thermal noise floor (for an assumed noise figure of 6.5 dB) is also plotted.

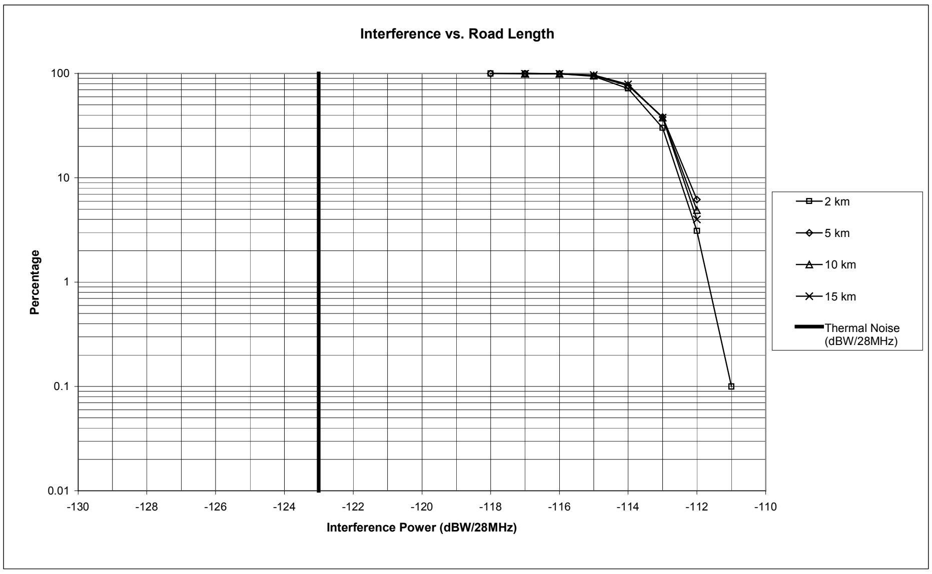

Figure 13: Aggregate Interference vs Road Length

The results show that the aggregate interference remains above the receiver thermal noise when the road length for which simulations are performed is varied within the range 2–15 km. In addition, differences in the aggregate interference levels are not significant, indicating that interference entries from nearby on-beam transmitters contribute significantly to the aggregate interference. In the case of very high interference levels (between -113 and -111 dBW/28MHz), differences are primarily attributed to the limited total number of simulation trials conducted (1000 trials corresponds to a minimum detectable probability of 0.1%).

A further analysis based on a 100% radar penetration rate has indicated that the aggregate interference levels are -109.886, -109.755, -109.745 and -109.742 dBW/28MHz for 2, 5, 10 and 15 km road lengths, respectively, suggesting that, above 2 km, an increase in the road length does not affect the aggregate interference significantly.

4.2.2.5 *Operating Frequency*

The interference analysis presented in this section aims to derive interference statistics for an assumed FS receiver operating frequency of 26 GHz. As illustrated in Figure 5, in the 26 GHz band, the receive antenna patterns are defined for Class 1 and 2.

The 4-lane interference scenario (see Figure 10) was simulated to derive interference statistics for Class 1 and 2 antennas. It is assumed that the FS receive antenna maximum gain is 40 dBi, the azimuth angle is 5° with respect to the direction of travel in the nearest lane and the receiver bandwidth is 28 MHz. Furthermore, the road length is considered to be 5 km together with a 50 m vehicle separation and the penetration rate is taken to be 40%. Vehicles are configured to be ‘cars’, each with four radars. Interference statistics obtained from 1,000 trials are compared against the FS receiver thermal noise power (for an assumed noise figure of 6.5 dB) in the following figure.

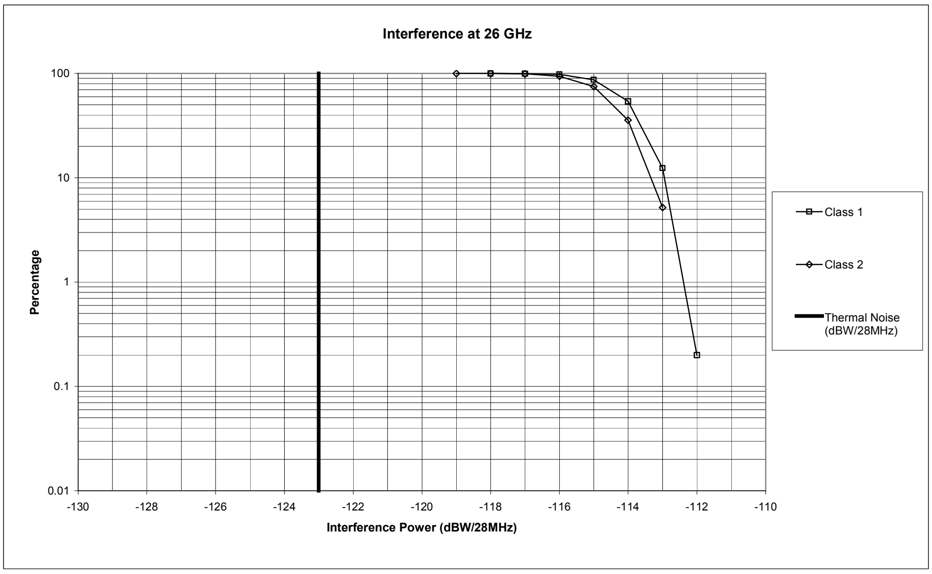

Figure 14: Aggregate Interference in 26 GHz

The aggregate interference is higher for the Class 1 antenna pattern for a given exceedence probability although the difference is small. The results are in line with the antenna patterns shown in Figure 5. In addition, the interference statistics of both patterns are well above the receiver thermal noise level, which suggests that the FS link unavailability will be increased to an unacceptable level.

4.2.2.6 *Receiver Bandwidth*

As stated previously (Section 3.2), the FS link receiver bandwidths are quoted to be in the range 3.5–56 MHz. A baseline figure of 28 MHz is employed in the interference scenarios presented in the preceding sections.

It should be noted that the use of different receiver bandwidths will not affect the analysis results. For example, if the receiver bandwidth is assumed to be halved this will reduce the aggregate interference by 3 dB. The receiver thermal noise power will also be reduced by the same amount. Therefore, ΔN (which is the relative increase in the noise power due to interference) will remain unchanged. This will then give rise to the same increase in link unavailability.

4.2.2.7 *Maximum Receive Antenna Gain*

The impact of maximum receive antenna gain is investigated by assuming that the receiver is operating at 23 GHz and employing a Class 2 antenna radiation pattern. Figure 15 illustrates the antenna envelopes for maximum gain values of 35, 40 and 45 dBi, for off-axis angles less than 10°. The antenna envelopes are the same for off-axis angles greater than 5°.

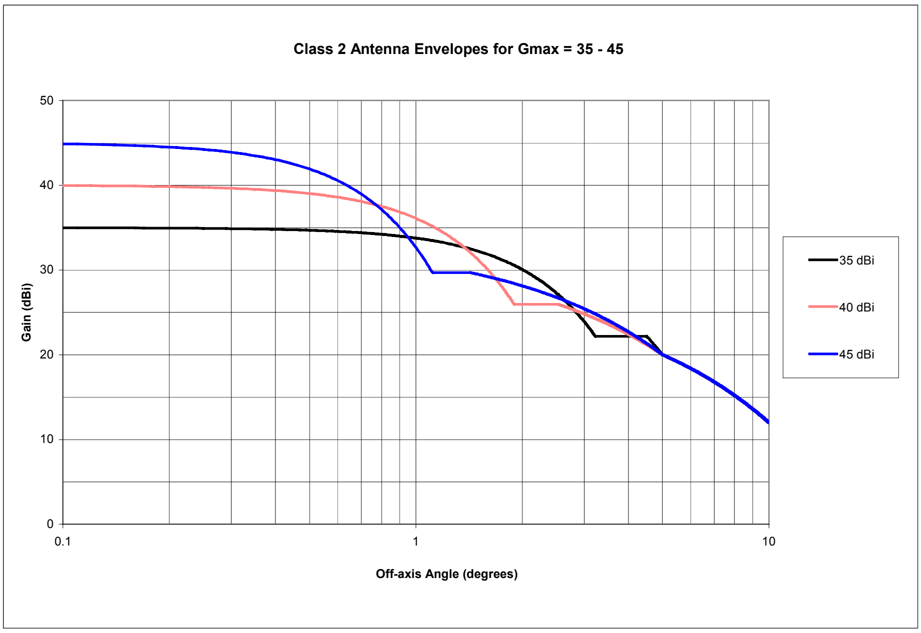

Figure 15: 23 GHz Class 2 Patterns for G_{max} = 35–45 dBi

The simulation model is the 4-lane interference scenario shown in Figure 10. The road length is taken to be 5 km and the vehicle separation is assumed to be 50 m. The vehicles use four radars (one on each side) and the penetration rate is 40%. As before, the FS receive antenna azimuth is taken to be 5°. Each simulation comprises 1,000 trials and the interference statistics shown in Figure 16 are compared against the receiver thermal noise floor, for an assumed noise figure of 6.5 dB.

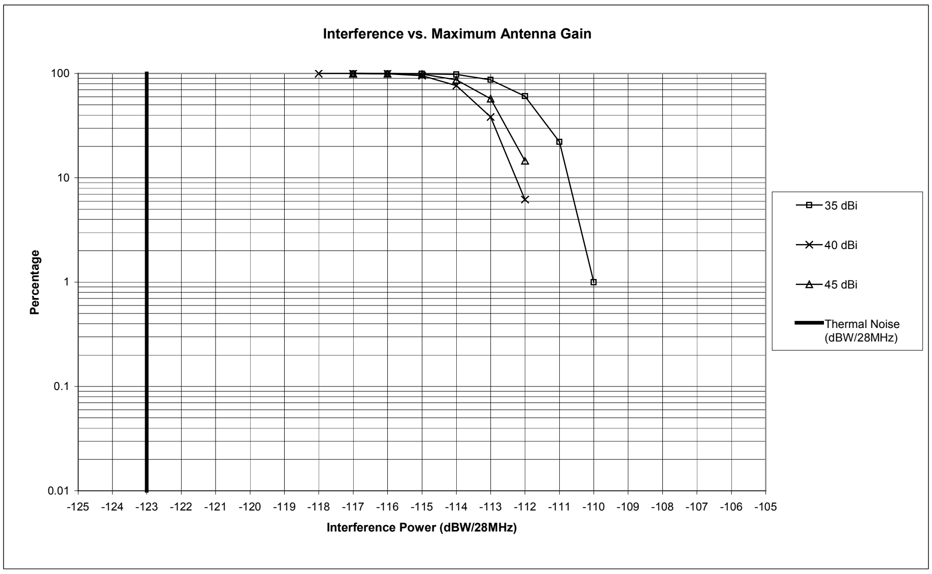

Figure 16: Aggregate Interference vs Maximum Gain

The maximum variation in the calculated aggregate interference is limited to 2 dB for a given exceedence probability. Therefore, the use of different maximum antenna gains does not have a significant effect on the possibility of sharing.

It is interesting to note that the results do not comply with the generic trend of 'an increasing gain leading to an increasing interference'. This is the result of the particular interference scenario considered. For a receiver azimuth of 5°, an antenna height of 10 m and a distance of 28 m from the centre of the road, the dominant interference entries fall into the off-axis region of around 2°, where the gain of the 35 dBi antenna is the greatest followed by that of the 45 dBi antenna as shown in Figure 15.

4.2.2.8 Separation Distance

The effects of vehicle separation distance are investigated using the same scenario as above. It is assumed that the receive antenna maximum gain is 40 dBi and the vehicle separation distances are 20, 50 and 100 metres. The results are compared against the receiver noise level of -123 dBW/28MHz in Figure 17.

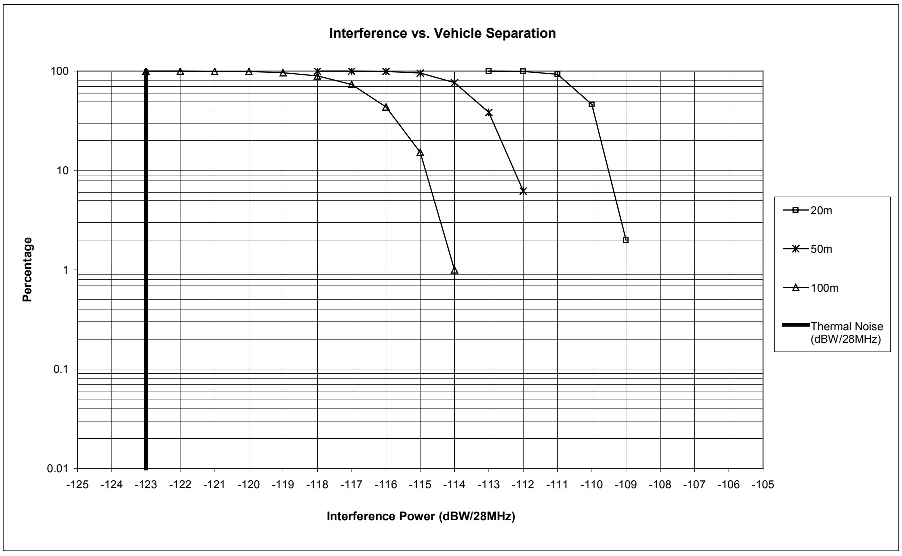

Figure 17: Aggregate Interference vs Separation Distance

For the assumed penetration rate of 40%, a decreasing separation distance results in an increasing aggregate interference. The results indicate that, for a given exceedence probability, the maximum increase in aggregate interference power is approximately 6 dB when the separation distance is reduced from 100 m to 20 m. It should be noted that, for all separation distances, the interference statistics remain above the receiver thermal noise level.

4.2.2.9 Receiver Height Above Road Level

So far, the interference scenarios have been based on the assumption that the FS receive antenna is 10 m above ground level. Using the 4-lane scenario (with a 40% penetration rate and a 50 m separation distance), the implications of the FS receiver height were investigated. Figure 18 shows the results for antenna heights of 5, 10, 20, 30 and 40 metres. It is worth noting that the FS receiver wanted path elevation angle is 0° for all antenna heights.

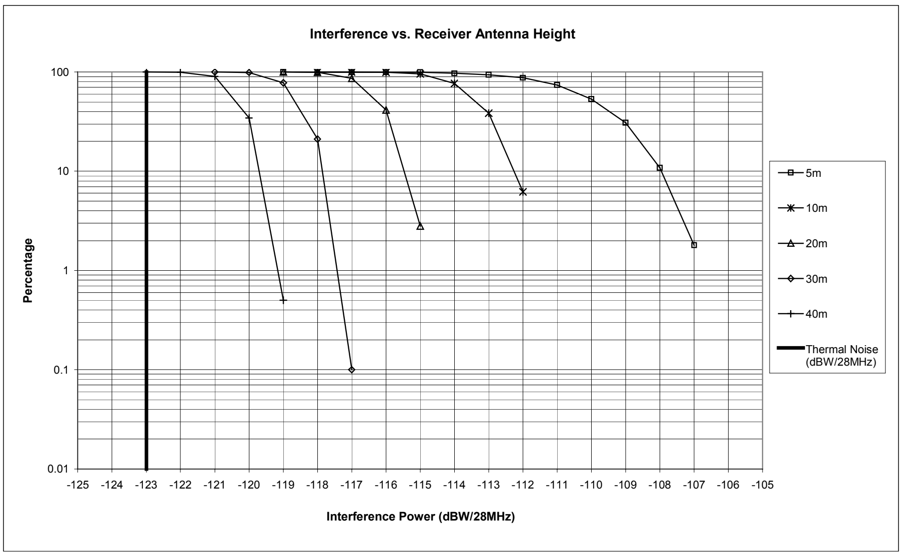

Figure 18: Aggregate Interference vs Receive antenna Height

For all heights considered, the maximum variation in the aggregate interference is approximately 12 dB, which corresponds to scenarios where the receive antenna is modelled to be at 5 m and 40 m above the road level. Despite this variation, the receiver thermal noise level is still exceeded at all antenna heights.

For a given exceedence probability, when the receive antenna height is increased the aggregate interference is decreased. An increase in the receive antenna height implies that the number of interference entries at the receiver will increase as some of the blocked paths may become visible. On the other hand, an increase in the receive antenna height will also imply that the off-axis angle at the receiver may increase for the near on-beam line-of-sight interference paths. The results shown in Figure 18 suggest that aggregate interference statistics are largely dependent on the near on-beam interference paths for which the receive antenna discrimination is increased with increasing antenna height.

This is explored in detail using the single entry interference analysis model. Assume that there is a single radar interfering with an FS receiver (pointing at 5° azimuth) at 5 and 10 metres above the road level. The following figure illustrates the single entry interference level obtained at every 50 m over a distance of 5 km (note that 0 m corresponds to the beginning of the 5 km road section considered).

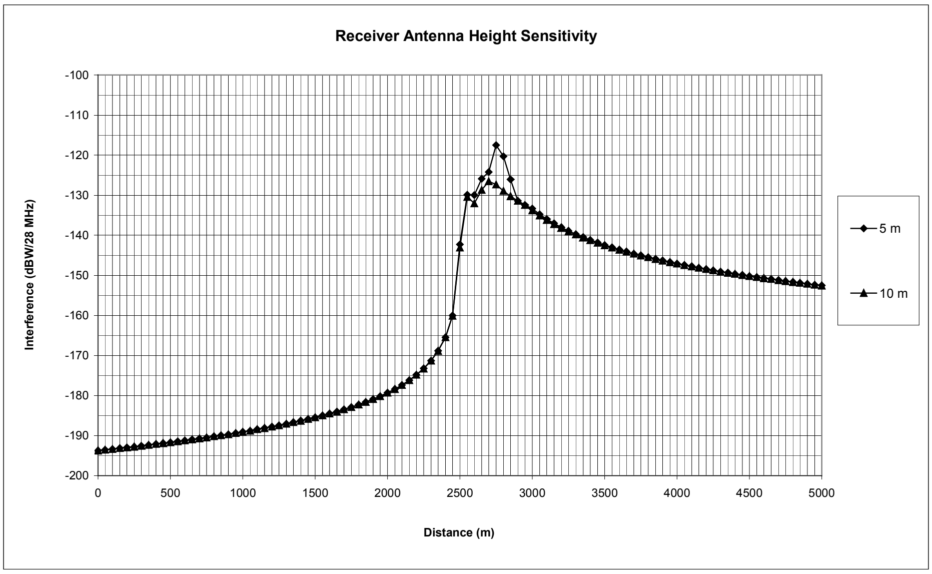

Figure 19: Single Entry Interference Levels

It is clear that, when the receive antenna is higher, interference levels at the FS receiver corresponding to near on-beam interference entries are reduced (due to an increase in off-axis angle). This, in turn, reduces the aggregate interference.

4.2.2.10 Receiver Distance to Roadside

As shown in Figure 10, the 4-lane interference scenario assumes that the FS receiver is located 20 m from the nearest lane. The sensitivity of the interference statistics to the distance from the roadside is examined for distances of 10, 20, 40, 75 and 100 m, assuming there are four radars per car and the radar penetration rate is 40%.

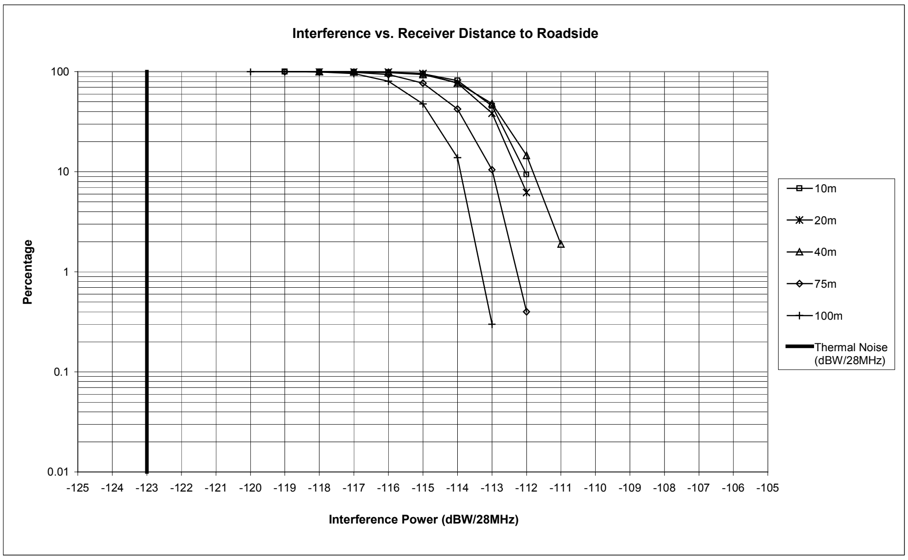

Figure 20: Aggregate Interference vs Receiver Distance to Roadside

For a given exceedence probability, the maximum variation in the aggregate interference statistics with the receiver distance to the roadside is approximately 3 dB, which is not significant as all calculated values remain well above the receiver noise power level.

Using the single entry interference model, the implications of varying the FS receiver distance to the roadside are examined further. The analysis is based on the assumption that there is a single radar interfering with an FS receiver (pointing at 5° azimuth and located at 10, 20, 40, 75 and 100 m from the roadside). The following figure illustrates the single entry interference level obtained at every 50 m over a road length of 5 km.

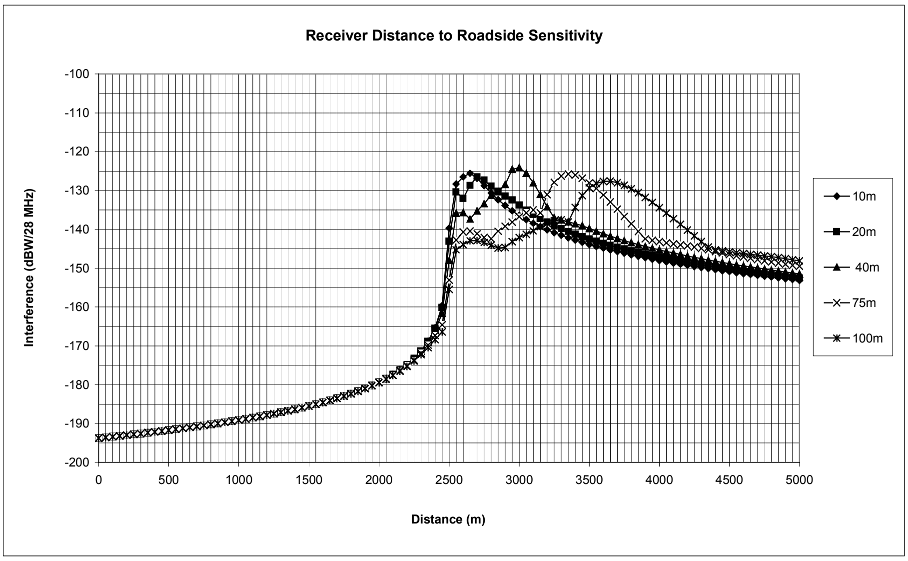

Figure 21: Single Entry Interference Levels

As can be seen, the maximum variation in the highest single entry interference is approximately 3.5 dB (when the distance to the roadside is 40 m the maximum interference is -124.12 dBW/28MHz and when the distance to the roadside is 100 m the maximum interference is -127.62 dBW/28MHz) which is in line with the 4-lane interference scenario results shown in Figure 20.

5 CONCLUSIONS

This report presents detailed analyses of sharing scenarios comprising UWB automotive radar transmitters interfering with FS point-to-point links (aligned with busy roads). For the large set of representative system parameter values examined, a general conclusion is that the aggregate interference from UWB radar transmitters will increase the FS link unavailability to an unacceptable level. This is largely due to vehicles in the nearest lane to the fixed link receivers, because radars located on the side of these vehicles are not affected by adjacent car blocking and interference paths are always line-of-sight.

The results of sensitivity analysis conducted on model parameters (including receive antenna pointing, antenna patterns, maximum antenna gain, vehicle shape, number of radars per vehicle, vehicle density, radar penetration rate, operating frequency, receive antenna height, road length and receive antenna location relative to road) suggest that variations in the aggregate interference statistics are not large enough, making sharing highly unlikely. In nearly all scenarios, aggregate interference is calculated to be above the receiver thermal noise which, in turn, results in the FS link unavailability increase threshold of 1% being exceeded by a very significant amount.

It should be noted that the results presented in this report take account of aggregation from line-of-sight interference paths only. In other words when a path from a radar transmitter is blocked it is assumed that there is no interference contribution. In practice, diffraction and scattering due to adjacent vehicles will result in interference even though there is no line-of-sight path between the transmitter and receiver. Within the limited timescale of this study, the implications of these effects have not been modelled. It is, however, reasonable to assume that interference from line-of-sight paths will dominate aggregate interference statistics and additional contributions due to diffraction (around 2 dB) and scattering (possibly up to 3 dB) will not significantly affect the results, which are already causing an unacceptable increase in FS link unavailability.

Including a UWB radar transmitter activity factor and the attenuation of interference paths due to road spray might reduce the aggregate interference. Typically, UWB radar transmitters will be not be transmitting for 100% of the time. Transmission periods will be followed by a data transfer and computation period during which there will not be emission. This may lead to a reduction in the average transmitted power by approximately 3 dB. Attenuation of interference paths due to road spray may also decrease interference by around 2 dB. In addition, attenuation due to foliage (including traffic signs, bridges, buildings and trees) may reduce the impact of interference paths to some degree (perhaps 5 dB).

During the course of this study, FS receive antenna radiation patterns based on an envelope of sidelobe peaks were used to examine the impact of aggregate interference from UWB radar transmitters. In practice, interference paths will arrive at the peaks and troughs of the actual receive antenna pattern. In order to take account of both peaks and troughs, ITU-R Recommendation 1245 has been developed. This recommendation defines an antenna pattern based on averaging the actual antenna peaks and troughs. Although the use of an averaged pattern will reduce the impact of interference through sidelobes, it will not affect the near on-beam interference entries, which dominate the aggregate interference level.

Many of the results presented in this report indicate that aggregate interference levels are of the order of 10 dB above the fixed link receiver thermal noise level. The ITU-R interference criterion requires the interference level be of the order of 20 dB below the fixed link receiver thermal noise floor in order to satisfy a low level of increase in fixed link unavailability. In order to facilitate sharing, it will clearly be necessary to reduce the 30 dB discrepancy. Given the magnitude of the discrepancy, it seems unlikely that any of the mitigation factors identified above will close the gap sufficiently by themselves.