REPORT ITU-R M.2112

Compatibility/sharing of airport surveillance radars and meteorological radar with IMT systems within the 2 700-2 900 MHz band

(2007)

1 Introduction

Recognizing need for additional spectrum for IMT systems, the band 2 700-2 900 MHz was identified as a candidate band for IMT systems, presenting potential advantages for IMT.

However, as described in the following table, the band 2 700-2 900 MHz is allocated worldwide on a primary basis to radionavigation service, used for air surveillance radars (ASR), including radars providing air surveillance and air traffic control, as well as meteorological radars that are afforded equal status to the aeronautical radionavigation system (ARNS) for operation in this band under RR No. 5.423.

Allocation to services		
Region 1	**Region 2**	**Region 3**
2 700-2 900	AERONAUTICAL RADIONAVIGATION 5.337 Radiolocation 5.423 5.424	

5.423 In the band 2 700-2 900 MHz, ground-based radars used for meteorological purposes are authorized to operate on a basis of equality with stations of the aeronautical radionavigation service.

5.337 The use of the bands 1 300-1 350 MHz, 2 700-2 900 MHz and 9 000-9 200 MHz by the aeronautical radionavigation service is restricted to ground-based radars and to associated airborne transponders which transmit only on frequencies in these bands and only when actuated by radars operating in the same band.

5.424 *Additional allocation:* in Canada, the band 2 850-2 900 MHz is also allocated to the maritime radionavigation service, on a primary basis, for use by shore-based radars.

Since ARNS radars perform a safety-of-life service as specified by No. 4.10 of the Radio Regulations (RR), harmful interference must be avoided. Thus, any potential new service introduced in this band must be thoroughly analyzed to ensure that interference does not exceed the radar protection criteria as given in Recommendation ITU-R M.1464.

It should be noted that this band was already considered as a potential extension band for IMT-2000 at WRC-2000 and that, compatibility studies performed at that time, based on available assumptions, concluded on the non-compatibility of co-channel operation between IMT-2000 and radiodetermination services.

The present Report provides compatibility analysis between ASR and meteorological radars and IMT systems operating in the 2 700-2 900 MHz band with new assumptions and systems characteristics.

2 Compatibility analysis

This Report contains two sharing studies given in Annex 1 (Study A) and Annex 2 (Study B).

Study A considers compatibility analysis between IMT systems and radars in both interference scenario from IMT stations to radars and radars to IMT stations. It first provides simulations that quantify interference levels from meteorological radars to IMT networks and discusses proposed interference mitigation techniques, including frequency dependent rejection analysis. Secondly, it provides a compatibility analysis of interference from IMT networks to ASR and meteorological radars that describe technical matters related to the methodology, protection criteria, and mitigation techniques used to analyze potential compatibility.

Study A (Annex 1) contains the following Appendices:

– Appendix 1 to Annex 1 summarizing the characteristics and assumptions used for the studies and taken from various ITU-R Recommendations (see § 3) (Radar and IMT system characteristics, interference criterion, propagation scenarios, simulation methodologies and interference mitigation techniques).

– Appendix 2 to Annex 1 providing results of IMT sharing studies with ASR's Type A, B and C as described in Recommendation ITU-R M.1464.

– Appendix 3 to Annex 1 presenting results of IMT sharing studies with meteorological radars Type G as described in Recommendation ITU-R M.1464.

– Appendix 4 to Annex 1 presenting results of studies that show what the impact of ASR and meteorological radar operations have upon IMT systems.

Study B (Annex 2) considers compatibility analysis between IMT systems and radars in both interference scenario from IMT stations to radars and radars to IMT stations. It provides simulations that quantify interference levels from IMT networks to meteorological and ARNS radars, including effects of mitigation techniques and frequency dependent rejection. Secondly, it provides a detailed analysis of interference to IMT networks from ASR and meteorological radars. Radar and IMT characteristics are described, as well as the methodology for the various simulations.

Study B contains the following Appendices:

– Appendix 1 to Annex 2 describing the clutter loss modifications to the propagation model for transmitters of low height.

– Appendix 2 to Annex 2 containing results on IMT base station front end filters, allowing increase of the frequency dependent rejection (FDR).

– Appendix 3 to Annex 2 presenting a detailed analysis of interference from radars to IMT networks.

3 References

[1] Recommendation ITU-R M.1464 – Characteristics of radiolocation radars, and characteristics and protection criteria for sharing studies for aeronautical radionavigation and meteorological radars in the radiodetermination service operating in the frequency band 2 700-2 900 MHz.

[2] Recommendation ITU-R M.1461 – Procedures for determining the potential for interference between radars operating in the radiodetermination service and systems in other services.

[3] Recommendation ITU-R P.452-12 – Prediction procedure for the evaluation of microwave interference between stations on the surface of the Earth at frequencies above about 0.7 GHz.

[4] Report ITU-R M.2039 – Characteristics of terrestrial IMT-2000 systems for frequency sharing/interference analyses.

4 Conclusion

From the studies attached to this Report, it can be concluded that IMT and radiodetermination services in the band 2 700-2 900 MHz operating on a co-frequency basis are not compatible, presenting large required separation distances of several hundred of kilometers, even applying the possible mitigation techniques considered to date.

Assuming a frequency management that would consider a frequency separation between IMT systems and radiodetermination radars, filtering characteristics of both IMT and radars could provide a certain interference level decrease (FDR of 50 dB). In this case, for meteorological radars (type G) the analysis still shows high separation distances and hence a non-compatibility in most of the cases:

– macro and micro IMT cells with or without potential practical mitigation techniques;

– pico cells without mitigation techniques.

For the other type of radars considered in the study (ASR, type A), the analysis shows that the separation distances would be decreased to tens of kilometers for pico cells and, provided that sufficient clutter attenuation could be ensured by adequate placing of the station, for IMT-Advanced micro cells.

The following mitigation techniques were considered:

– *Improved filtering of IMT emissions from 50 to 90 dB*: In this case, filtering could provide an additional interference reduction of about 15 dB when considering frequency separation of 10 MHz between IMT stations and radars. In this case, separation distances would be further reduced. It was shown that for IMT-Advanced micro cells, the required separation distance is decreased down to 3 km for ASR radar whereas it still remains beyond 100 km for meteorological radars.

This improved filtering could further reduce the interference (with FDR up to 90 dB) if considerably larger frequency separation between IMT stations and radars are applied. However, in this case, it could be considered that the required frequency separation would not be compatible with successful operation of radars and IMT in a 200 MHz band.

– *IMT Sector blanking*: This mitigation technique only applies to sectorised IMT macro cells and could potentially reduce the interference up to about 30 dB, resulting in separation distances of about 150 km for meteorological radars and 10 km for ASR radars. However, this mitigation technique will be less efficient in a scenario with multiple radars present operating in the same frequency range.

– *Temporary muting*: This mitigation technique could theoretically reduce the interference by about 50 dB but was shown as being impractical since it is unlikely that IMT stations could either sense the radar antenna main beam direction or to receive this information from the radar networks.

It should be stressed that the potential use of the 2 700-2 900 MHz band by IMT should be limited to IMT systems downlink to avoid any possible interference from IMT handset/terminal that could not be controlled by the network in case of malfunction. This leads to the point that uplink would have to be accommodated in another band.

In addition, due to frequency separation constraints with radars, there would be a limit on the possible bandwidth available for IMT connections in this band, acknowledging that it would be challenging to manage 20 MHz IMT bandwidth between radar frequencies, depending on radar deployment density, and impossible to handled 100 MHz bandwidth in this 200 MHz frequency band.

It should also be noted that, in addition to necessary frequency separation between IMT and radars, radar frequency tolerance given in RR Appendix 2 are approximately of about ± 3.5 MHz in the 2 700-2 900 MHz band which would effectively require a frequency separation higher than 15 MHz.

Also, one should consider that a number of radars in this frequency band operate on 2 fixed frequencies or in a frequency hopping mode.

Should the 2 700-2 900 MHz band be considered for use by IMT systems, such use could be constrained or even impossible depending on the radar deployment density. In countries with low radar deployment, there could be frequency ranges and geographical areas where some types of IMT systems downlink may be accommodated.

It should be highlighted that possible frequency separation management between radars and IMT systems in this band would restrict future radar deployment that could be needed for improving radar networks coverage required for safety of life and security purposes.

5 Definitions and abbreviations

5.1 Definition

No new definitions introduced.

5.2 Abbreviations

ACLR Adjacent channel leakage power ratio

ACS Adjacent channel selectivity

ADC Analog to digital converter

AGC Automatic gain control

ARNS Aeronautical radionavigation system

ASR Air surveillance radar

BER Bit error rate

CDF Cumulative distribution function

CDMA Code division multiple access

DFS Dynamic frequency selection

FDR Frequency dependent rejection

FEC Forward error correction

GHz Gigahertz

IMT International mobile telecommunications

IPS Integrated propagation system (computer model)

ITU International Telecommunication Union

kHz	Kilohertz
km	Kilometres
LNA	Low noise amplifier
LoS	Line-of-sight
MHz	Megahertz
NLOS	Non line-of-sight
NTIA	National Telecommunications and Information Administration
OFDM	Orthogonal frequency division multiplexing
OFR	Off tune rejection
OoB	Out of band
OTR	On tune rejection
PRR	Pulse repetition rate
SF	Spreading factor
SDMA	Spatial division multiple access
UMTS	Universal mobile telecommunications system
WMO	World Meteorological Organization

Annex 1

Study A
Compatibility of air surveillance radars and meteorological radar with IMT systems within the 2 700-2 900 MHz band

1 Introduction

The band 2 700-2 900 MHz is allocated worldwide on a primary basis to ASR, including radars providing air surveillance and air traffic control. In addition, meteorological radars are afforded equal status to the ASR for operation in this band. Since ASR radars perform a safety service as specified by RR No. 4.10, harmful interference must be avoided. Any other service introduced in this band must be thoroughly analyzed to ensure that interference is kept at acceptable levels and to prevent any compromise in the quality of radar services in those countries using this band for the ASR and meteorological radars. About 40 administrations worldwide have been identified that operate meteorological radars in the band 2 700-2 900 MHz for both air surveillance and meteorological radar operations. While some administrations have low numbers of systems in operation, the use of radars in the 2 700-2 900 MHz band near the borders of neighbouring countries must be considered as well when determining the availability of spectrum by coordination in case large separation distances are required. For many administrations that currently do not use the band or use the band lightly, future additional air surveillance radars and meteorological radars should be taken into account.

However, the importance of additional spectrum for IMT has been recognized, and the band 2 700-2 900 MHz has a number of advantages for IMT:

– this band is near the bands already identified for IMT-2000, which may facilitate the use of some of the base and mobile station hardware as in the band 2.5-2.69 GHz and would present similar propagation conditions; it is adjacent to the IMT-2000 extension band 2 500-2 690 MHz simplifying development and manufacture of equipment resulting in economy of scale and thus has added benefits for the developing countries;
– the propagation characteristics are more favourable than in the upper parts of the bands of 3-5 GHz.

Furthermore, the plan for IMT deployment in this band is expected to be between years 2015-2020. The exact timeline will depend on market needs and the various administrations' requirements. At present, it is necessary to continue analysing the coexistence of ASR and meteorological radars with IMT systems. Please refer to the conclusion of the report for a more detailed description of where additional studies are needed.

2 Executive summary

This contribution provides a compatibility analysis between air surveillance and meteorological radars and IMT systems operating within the 2 700-2 900 MHz band. The analysis is based on simulations that quantify interference levels between air surveillance and meteorological radars and IMT base station to mobile links. This contribution also includes an operational analysis of several proposed interference mitigation techniques that is in part based on frequency dependent rejection analysis.

3 Scope

This study provides a compatibility analysis between air surveillance radars (ASR) and meteorological radars and IMT systems in the 2 700-2 900 MHz band. It describes technical matters related to the methodology, protection criteria, and mitigation techniques used to analyze potential compatibility. Details that describe the IMT and radar characteristics, ASR and meteorological radar interference criteria and IMT interference criteria used for the studies discussed in this text were taken from various ITU-R Recommendations and are summarized in Appendix 1 to Annex 1 – Study A Compatibility of air surveillance radars and meteorological radar with IMT systems within the 2 700-2 900 MHz band. Appendix 2 to Annex 1 provides results of IMT sharing studies with ASR's Types A, B and C radars as defined in Recommendation ITU-R M.1464 within the 2 700-2 900 MHz band. Appendix 3 to Annex 1 presents results of IMT sharing studies with meteorological radars as defined in Recommendation ITU-R M.1464 Type G within the 2 700-2 900 MHz band. Appendix 4 to Annex 1 present results of studies that show what the impact of ASR and meteorological radar operations have upon IMT systems operating within the 2 700-2 900 MHz band. Annex 2 presents the results of additional sharing studies that incorporate interference mitigation techniques. Appendix 1 to Annex 2 describes the analysis methodology that was used for those studies.

4 Overview of study results

4.1 IMT interference criteria levels

Studies have shown that interference from ASR's and meteorological radars into IMT systems temporarily exceeds IMT protection criteria levels.

4.2 Required ASR and meteorological radar separation distances based on radar protection criteria levels

The results of the co-channel sharing studies between an IMT macro, micro and pico cell environment of base stations and air surveillance and meteorological radars show that IMT networks exceed the protection criteria for very large distances. Co-channel studies have also shown that separation distances vary as a function of cell topology, service deployment methodology and radar types. The study results outlined in Appendices 2, 3 and 4 to Annex 1 and Appendix 1 of Annex 2 have shown that separation distances of greater than 500 km are required in most cases in order to not exceed the ASR and meteorological radar protection criteria by IMT systems.

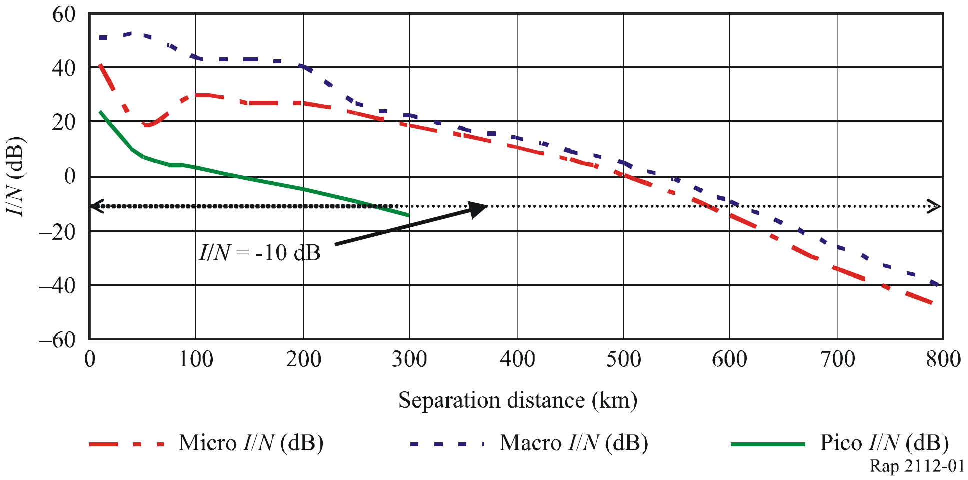
Figure 1 illustrates the effect that increasing separation distances between an IMT service area and Type G meteorological radar has upon *I*/*N* protection criteria when terrain variations are encountered.

In this particular simulation, a terrain model was used that initially placed the IMT system on a relatively low lying flat plain. As the radar system was moved to the west of the IMT system, a gradual decrease in the interference level and the subsequent *I*/*N* value was noted. At around 75 km west of the IMT system, the terrain started to rise as did the interfering signal level to the radar from the IMT system. This was due to a clearing of a line of site path from the radar to the IMT system. This resulted in increased interference and *I*/*N* levels for the macro and micro cell topologies. A smooth earth model was used for the pico cell analysis. Consequently, the pico cell results were not impacted by the nature of the terrain. Similar results can be expected for the ASRs.

As can be seen in Fig. 1, an acceptable *I*/*N* value (< –10 dB) for the macro cell topology was reached when the radar was 610 km away from the IMT system. An acceptable *I*/*N* value (< –10 dB) for the micro cell topology was reached when the radar was 580 km away from the IMT system. An acceptable *I*/*N* value (< –10 dB) for the pico cell topology was reached when the radar was 270 km away from the IMT system.

FIGURE 1

***I*/*N* vs. separation distance**



If one were to deploy an IMT network on a shared basis with ASR's and meteorological radars in this environment, a separation distance of 610 km would be required in order to protect the meteorological radar from interference from the IMT network. Additional simulations yielded similar result for ASR's when using this terrain model.

Terrain plays an important role in determining the separation distances required to protect radars from interference from IMT systems and cannot be ignored when conducting sharing studies. Since the terrain profile between the transmitter and the interfered receiver may influence propagation considerably, leaving such information out may results in erroneous calculations of propagation loss and consequently erroneous interference levels which may be either too high or too low.

Table 1 summarizes the minimum separation distances required to prevent IMT-Advanced systems from exceeding the ITU recommended protection criteria for ASR and meteorological radars as a function of cell topologies and radar types as defined in Recommendation ITU-R M.1464.

TABLE 1

Minimum IMT-Advanced to air surveillance and metrological radar separation distances (km)

	Cell topology		
Radar type	**Macro (km)**	**Micro (km)**	**Pico (km)**
Type A	595	575	290
Type B	595	575	300
Type C	595	575	290
Type G	600	575	270

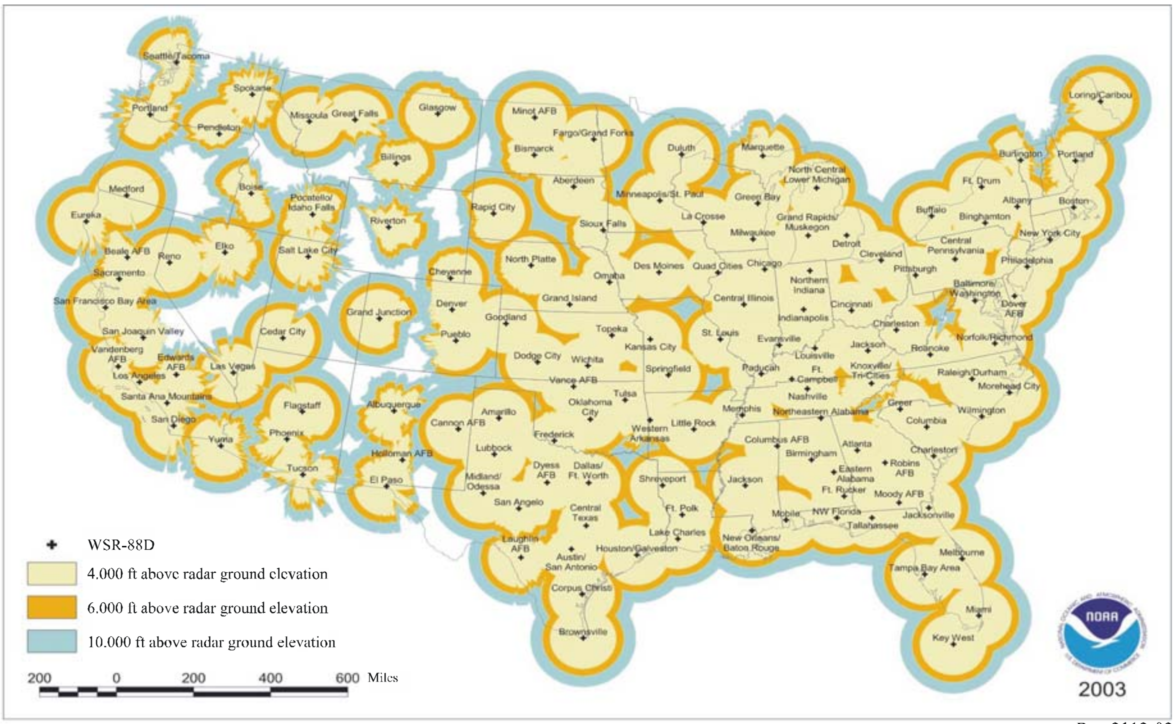
NOTE 1 – Worst case separation distances were summarized in Table 1. The separation distances that were derived in Annex 2 were typically on the order of > 200 km or more, confirming, in lieu of the application of any interference mitigation techniques, the need for large separation distances between radars (air surveillance and meteorological) and IMT systems.

Radars in the 2 700-2 900 MHz band are often operated within or near cities. Separation distances of this magnitude would preclude the deployment of all types of mobile service in the same band in areas within cities.

Even if such separation distances could be tolerated, regions in which sharing could take place may be severely limited due to the wide spread geographical deployment of ASR, meteorological and other radar systems. It is important to note that the ranges the meteorological radar processes data and provides information out to, reflectivity: 460 km, and radial velocity and spectrum width: 230 km (this will increase in April 2008 out to 300 km). Any co-channel IMT system located within those ranges will interfere with the radar’s ability to process data. Figure 2 illustrates the overlapping nature of a network of one administration’s network of meteorological radars. The nature of this network would limit the geography in which IMT systems could be deployed. The available geography becomes even further limited when ASR’s are included in the geographical coverage analysis. It should be noted, however, that Fig. 2 does not contain information about the frequencies used by the radars. It may thus be possible for IMT networks to utilize those frequencies that are not being used by the nearest radar station.

FIGURE 2

Meteorological radar network coverage map



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The approximate nominal values for radar coverage, bottom of beam, for flat terrain:

4 000 ft above ground level (AGL): 80 miles

6 000 ft AGL: 100 miles

10 000 ft AGL: 135 miles

4.3 Utilization of the 2 700-2 900 MHz band (Impact on IMT systems)

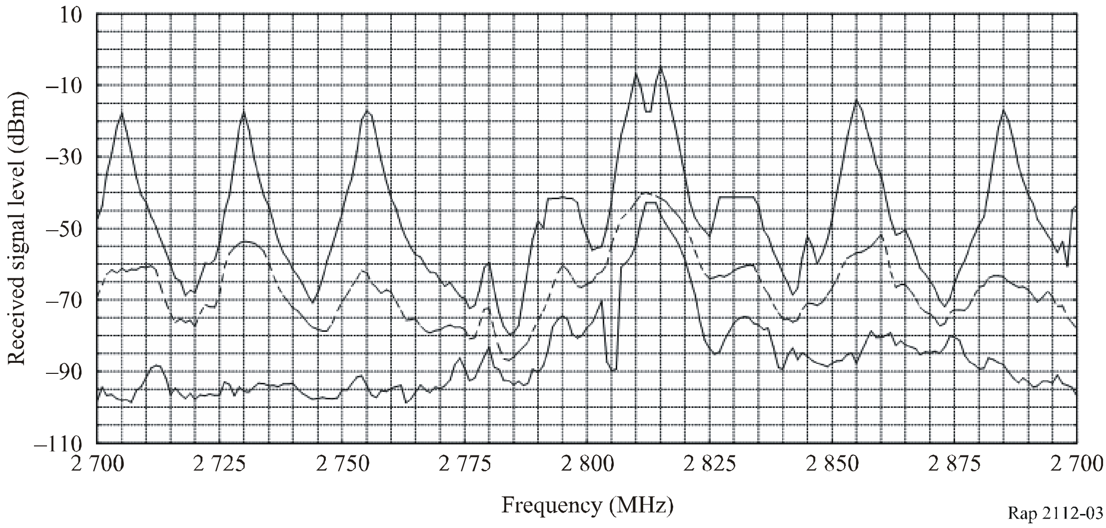
The extensive use of the 2 700-2 900 MHz band by ASR, meteorological, and other radar systems creates an RF environment in which IMT mobile or base station receivers could be jammed or damaged by the aggregate effect of the radar systems operating within that band. Figure 3 illustrates the frequency domain representation of the 2 700-2 900 MHz band as measured from a single site located several miles outside of the city of Los Angeles, California.

The upper most line in the graphic shows frequency in megahertz on the x-axis vs. received signal level. The data presented in this graphic show the maximum, minimum, and average (represented by the dotted line) measured power levels of received signals. Refer to NTIA Report 97-336 for more details. The accumulative measurement time during the survey was typically several hours, spread uniformly over the diurnal cycle and taken on the summit of one of the San Gabriel Mountain peaks in the Angeles National Forest just north of Los Angeles. The data represents a statistical sampling of the activity in the radio spectrum in the Los Angeles metropolitan area. Even if frequencies within the band where available to operate an IMT system, the bandwidth limitations and the separation distances that would be required to protect both the radar and IMT system would preclude the effective operation of both networks within the same band of frequencies.

Figure 3 may also represent spectrum available for IMT networks in this particular spot, or in a similar location in Los Angeles. Considering that the output power from, say, a micro base station may be as much as 60 dB lower than that of a radar, and may also be deployed in a more sheltered spot decreasing the amount of interference. Figure 3 shows that parts of the frequency band analyzed could be used for IMT base stations without exceeding radar protection criteria of *I*/*N* of –10 dB.

FIGURE 3

Frequency domain representation of the 2 700-2 900 MHz band within an urban environment (Los Angeles, California)



Radio frequency characterization studies of urban environment such as the one shown in Fig. 3, show that the aggregate power levels received by the IMT devices could result in interference to multiple mobiles and base stations.

Depending on the channel bandwidth and the distribution of service within the band, an off-set frequency operation may be possible; however additional studies will have to be done to conclusively prove if off-set frequency operation is possible.

4.4 Application of interference mitigation techniques

In some sharing studies it was suggested that separation distances can be reduced through the application of interference mitigation techniques such as antenna placement, orthogonal polarizations, adaptive antennas, filtering techniques, power control, and other site engineering techniques (e.g. clutter, building penetration loss, etc.). These types of mitigation techniques are effective in mitigating interference between adjacent cell sites within 2nd and 3rd generation mobile telephony systems. Annex 2, § 7.3 presents analyses of various IMT to radar interference mitigation techniques.

It has been suggested that radars would only be interfered with for a short period of time as the radar beam passes through the service area. This is not the case. Radar target returns are processed individually in at least two dimensions, range and azimuth. Radar receiver processing in these two dimensions forms resolution "cells" which are evaluated for the presence of radar pulses returned from targets. Interfering IMT signals, even if present for only short periods of time, can corrupt these resolution cells and will cause false or lost targets. If IMT systems are co-located within multiple service areas, radars will encounter interference from many IMT base and mobile stations. One should note that interference effects cannot be averaged over an entire rotation. Radar results must be accurate for every direction and for every distance, and it is therefore not acceptable to trade high interference in one direction for low interference in another by an averaging process. It is also possible that the aggregate IMT interference into the radar will appear as noise to the radar raising the constant false alarm rate (CFAR) and causing detection loss of targets.

5 Conclusions

The overall conclusions drawn from the results of this study with respect to effectively sharing the 2 700-2 900 MHz band between IMT devices and ASR, meteorological and other radar systems are:

a) The 2 700-2 900 MHz band is extensively used for meteorological and other radar systems creating an environment in which:

   – For co-channel operation, RF emissions from IMT transmitters would necessitate separation distances well in excess of 200 km in order to ensure that radar receiver interference criteria are not exceeded.

   – The operation of IMT receivers could be impaired, by the aggregate RF effect of the radar systems operating in that band.

   – In scenarios where the band use is limited to uni-directional (base station to mobile station) transmissions only, the IMT "victim" receivers would be the mobile stations that were communicating with various base stations throughout a given service area. High power radar stations will cause co-channel interference to IMT terminals even at large distances, however, radar interference is intermittent and the resulting QoS degradation in the IMT network has not been sufficiently studied and may need additional analysis.

b) The required separation distances up to several hundred kilometers for sharing of the band preclude the co-channel deployment of IMT systems and radars.

c) Interference to IMT receivers originating from high power radars with intermittent transmission is different from that originating from IMT transmitters. Consequently the special characteristics of radars need to be taken into account when analyzing radar to IMT interference. Due to the high output power of the radar the interference may affect various parts of the receiver chain (LNA, AGC, etc.) negatively. Effects may include transition periods for low noise amplifier (LNA) and automatic gain control (AGC) after the radar pulse during which performance is degraded, or even physical damage. Mitigation techniques may be included in the design phase to mitigate these effects, see Annex 2, § 7.3, for further discussion. It should be noted that interference from radar to IMT exceeds the established interference criteria even at large distances. However, the influence of the pulsed characteristics of radar interference, resulting in periods of silence that are long in relation to the active periods, have not been taken into account in this analysis. The affects of coding and interleaving have thus not been considered. See Annex 2, § 7.2 for a different analysis of this.

d) Even if the IMT service were offset in frequency from one radar system, the IMT systems may still be interfered with by other nearby geographically located radar systems operating at different frequencies throughout the band.

Appendix 1
to Annex 1

Air surveillance radars, meteorological radars and IMT system characteristics, propagation scenarios, simulation methodologies and interference mitigation techniques

1 Parameters of IMT systems

The IMT parameters were obtained from Report ITU-R M.2039. Table 2 contains a summary of those parameters. The adjacent channel leakage ratio (ACLR) parameters were obtained from 3GPP 25.104. Where applicable, a typical IMT Wideband CDMA system channel spacing/separation of 5 MHz was chosen. The overall assumption, however, is that apart from varying bandwidths; IMT-Advanced characteristics will be very similar to those of IMT-2000 as shown in Table 3.

TABLE 2

Power and antenna characteristics of IMT-2000 macro, micro and pico base stations

	Macro BS	Micro BS	Pico BS
Output power (dBm)	43	38	24
Antenna main beam gain (dBi)	17	5	0
Antenna height	30	5	1.5

The IMT parameters used in these studies were discussed, agreed, and finalized during the 19th WP 8F meeting, May 2006. In the case of ACLR, an extension of IMT parameters was used. Table 3 contains those parameters. The channel spacing for IMT systems was selected to be 10 MHz. The output power is given as effective isotropically-radiated power (e.i.r.p.) density range, with a maximum allowed transmitted power including antenna gains and feeder losses. Power levels were set to the maximum allowed levels of 43 and 38 dBm respectively for macro and micro base stations.

TABLE 3

Power and antenna characteristics of IMT-Advanced macro and micro

	Macro BS	Micro BS
e.i.r.p. density range, scaled to 1 MHz bandwidth	39-46 m/MHz	15-22 dBm/MHz
Antenna main beam gain (dBi)	17	5
Max transmit power + antenna gain – feeder loss (dBm)	59	35
Antenna height (m)	30	5
ACLR, 1st adjacent (dB)	45	45
ACLR, 2nd adjacent (dB)	50	50

Although Report ITU-R M.2039 specifies a pico antenna height of 1.5 m, the study took into consideration that pico base stations could also be installed inside tall buildings; as a result, an antenna height of 10 m was used in this study. In practice, variations in pico cell antenna heights are expected.

2 Air surveillance and meteorological radar parameters

Information and characteristics for the radars included in this sharing study were obtained from Recommendations ITU-R M.1461 and ITU-R M.1464. These Recommendations include information on air surveillance (Type A-F) and meteorological (G and H) radars. The relevant radar parameters for this study are summarized in Table 4.

TABLE 4

Radar system characteristics

	Air surveillance (Radar A)	**Air surveillance (Radar B)**	**Air surveillance (Radar C)**	**Meteorological (Radar G)**
Antenna rotation rate (degrees/s)	75	75	75	18
Radar receiver emission bandwidth, 3 dB (MHz)	5	0.653	15	0.600
Transmitter power, *P* (dBW)	62	61	44	57
Antenna main beam gain (dBi)	33.5	33.5	34	45.7
Antenna beamwidth (degrees)	1.35	1.3	1.45	0.92
Antenna sidelobe levels (dBi)	7.3	7.3	9.5	20
Antenna height (m)	8	8	8	30

The simulation was configured to closely approximate the operation of the radar. Antenna rotation was also included since it provides one of the important radar to IMT interference details used in the analysis. The level of interference, is defined by the protection criteria of $I/N = -10$ dB. This corresponds to a signal level of –153 dBW which takes into account multiple radars operating in the same band and represents a worst case scenario. An antenna height of 8 m for radar types A, B and C, and 30 m for radar type G were used in these sharing studies. An interference mitigation technique that has been used in past analyses[1] is radar antenna tilt.

ASR's are crucial systems that facilitate the safe and efficient operation of air travel worldwide. Meteorological radars provide immediate meteorological and hydrological information used to predict severe weather events. Both systems protect lives and property. ASR and meteorological radars cannot be limited to specific upward antenna tilt to avoid interference from IMT devices. ASR and meteorological radars require 360° visibility and ≤ 0 to 90° of elevation to properly perform their mission. To limit the elevation and azimuth range would prevent the radars from meeting mission objectives, and in the case of meteorological radars may render them completely

[1] ITU-R study on co-existence between air surveillance systems, meteorological radar and terrestrial IMT in the band 2 700-2 900 MHz.

useless. The sharing studies discussed in Appendix 2, 3 and 4 to Annex 1 considered IMT mobile and base station interference into radar stations of type A, B, C, and G.

3 IMT radio interface interference criteria

Report ITU-R M.2039 provides the interference criteria for the IMT radio interfaces. The interference criteria are listed in Table 5.

TABLE 5

Interference criteria for IMT radio interfaces

Radio interface	Interference criteria – Base stations	Interference criteria – Mobile stations
CDMA-2000 1X	–114 dBm per 1.25 MHz	–110 dBm per 1.25 MHz
CDMA-2000 3X	–109 dBm per 3.75 MHz	–105 dBm per 3.75 MHz
UWC-136 30 kHz	–131 dBm per 30 kHz	Unknown
UWC-136 200 kHz	–123 dBm per 200 kHz	Unknown
TD-CDMA	–115 dBm per 3.84 MHz	–111 dBm per 3.84 MHz
W-CDMA	Not studied	Not studied

Because Report ITU-R M.2039 did not provide criteria for allowable percentage of interference time, it was not taken into consideration in the radar to IMT interference analysis section. This aspect needs further study. According to Recommendation ITU-R M.1464, an I/N of –10 dB was used as the radar protection criteria for both the air surveillance and meteorological radars.

The formula describing the simulation calculation of the interference from a single IMT transmitter is as follows:

$$I\ (\text{dBW}) = PTX\ (\text{dBW}) + GTX\ (\text{dBi}) - LP\ (\text{dB}) + GRX\ (\text{dBi}) - FDR\ (\text{dB}) \qquad (1)$$

where:

I: interference at the radar receiver

PTX: transmitter power of the IMT station

GTX: antenna gain of the IMT station

LP: path loss between IMT station and radar (consider LoS, diffraction, troposcatter, and ducting in accordance with Recommendation ITU-R P.452. May also include building penetration loss in case of pico cells)

GRX: antenna gain of radar in direction of IMT station

FDR: frequency dependent rejection (applicable where IMT emission bandwidth is wider than the radar receiver passband).

Frequency dependent rejection (FDR) is comprised of two components, on-tune rejection (OTR) and off-frequency rejection (OFR). This analysis assumes that the IMT systems and the radar are operating co-channel. No adjacent channel analysis was conducted. OFR is the correction factor used when two operating frequencies are not the same, but transmitter and receiver bandwidths overlap. OFR is set to zero. OTR, the correction factor applied when the emission bandwidth is wider than the receiver bandwidth, applies when the IMT emission bandwidth exceeds the passband of the radar receiver. Refer to Recommendation ITU-R SM.337 for additional information on FDR, OTR and OFR.

The equations applicable to this analysis are:

$$FDR \text{ (dB)} = OTR \text{ (dB)} + OFR \text{ (dB)} = OTR \text{ (dB)} + 0 \text{ dB, when } BWIMT > BW\ RADAR \quad (2)$$

or

$$= 0 \text{ dB} + 0 \text{ dB}, \qquad \text{when } BWIMT < BW\ RADAR \quad (3)$$

Using equations (1), (2) and/or (3) for each IMT to radar interference path, the total interference (ITOTAL) from a network of N IMT stations can be determined. The formula for calculation of the total interference is:

$$ITOTAL \text{ (W)} = I1 \text{ (W)} + I2 \text{ (W)} + ... + IN \text{ (W)} \quad (4)$$

where:

ITOTAL: total interference power at the radar receiver

*I*1: interference power from Station No. 1 calculated from Equation 1 based on path specific conditions

*I*2: interference power from Station No. 2 calculated from Equation 1 based on path specific conditions

IN: interference power from Station No. *N* calculated from Equation 1 based on path specific conditions.

4 Propagation model

The sharing analysis of interference from an IMT network into the radars was conducted using a terrain modelling simulations that included software implementation of Recommendation ITU-R P.452. All propagation mechanisms that could contribute to interference in links were considered. (LoS, diffraction, troposcatter and ducting.) This study used the frequency range of 2 700-2 900 MHz. The percentage of time that radars could be interfered with was set to 0.001% to ensure minimum interference to radars and to enable Recommendation ITU-R P.452. An area just outside Washington D.C. was chosen as the terrain model. A smooth earth model was used in the pico cell simulation.

5 Deployment scenarios studied

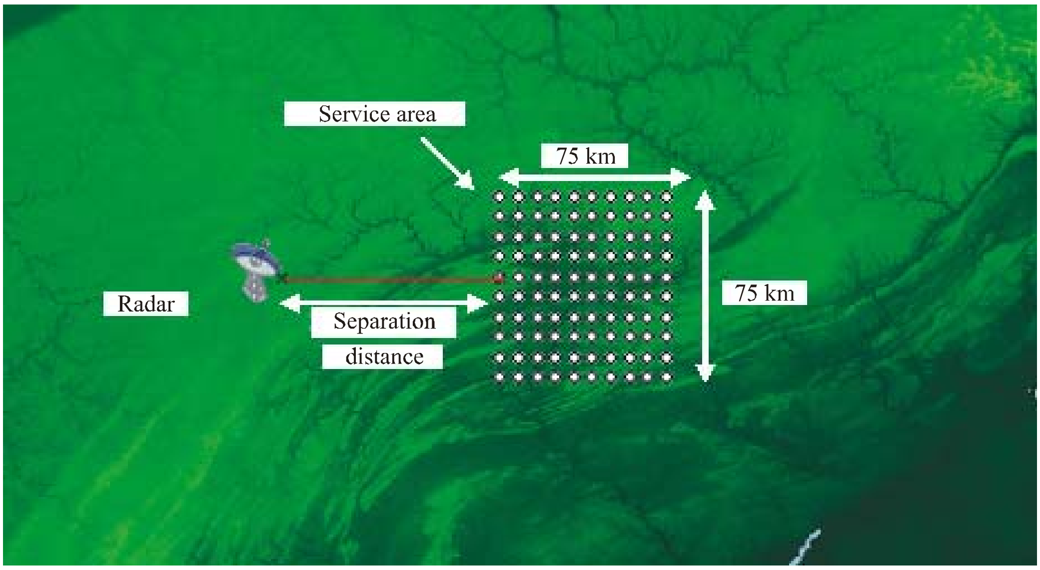
The predominant interfering element in an IMT network is the IMT base station. As a result, this study only examines the interference to ASR and meteorological radars from IMT macro, micro and pico base stations. In an actual deployment scenario a given service area would be made up of both base and mobile stations. Given that the interference level from base stations alone is sufficient enough to exceed both the ASR and meteorological radars protection criteria, there was no need to study the individual impact that mobile stations alone or mobile stations in conjunction with base stations would have upon ASR and meteorological radars.

5.1 Macro cell deployments

A macro cell is defined in this study to have average cell radius of 1 km as outlined in Report ITU-R M.2039. In this study, a macro cell coverage area of 75 km × 75 km was established. The simulation was run with the radar placed at the edge of the macro cell coverage area. Subsequent runs of the simulation varied the distance from which the radar was offset from the macro cell area. This scenario simulates the situation where the radar is located outside the main urban area of the city (refer to Fig. 4). It was assumed that one IMT base station transmitter emission for each cell was co-channel with radar receiver.

FIGURE 4

Radar operation outside of a city



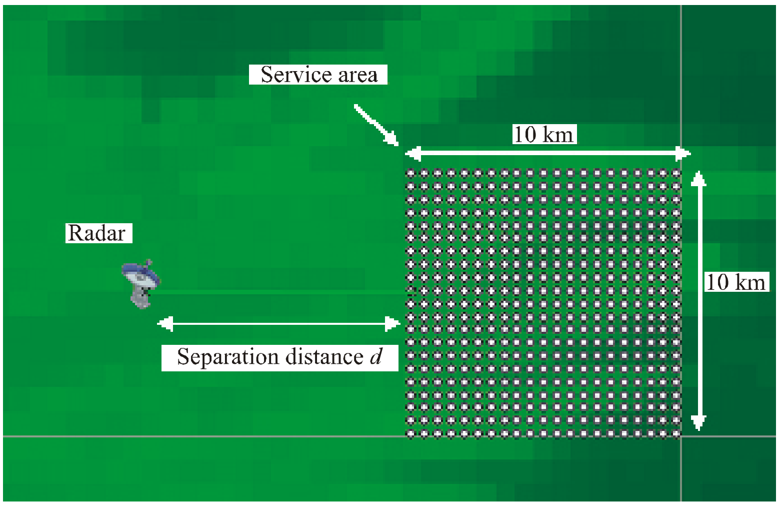
Rap 2112-04

5.2 Micro cell deployments

Micro cell configuration is intended to provide high-density use to vehicular and pedestrian traffic. A micro cell is defined in this study to have average cell radius of 315 m as outlined in Report ITU-R M.2039. In this study, a micro cell coverage area of 10 km × 10 km was established. The total micro cell service area was set to 10 km × 10 km. The micro cell service area would typically be small and limited to central city areas. Establishing an exclusion zone within a small service area (10 km × 10 km in this case) is not feasible. The probability of having a radar located in a central business district is small. . The simulation was run with the radar placed at the edge of the micro cell coverage area. Subsequent runs of the simulation varied the distance between the radar the micro cell area. Calculations were performed only in a configuration where the radar was offset from the service area (Fig. 5). It was assumed that one IMT base station transmitter emission for each cell is co-channel with the radar receiver.

FIGURE 5

Radar is offset from micro cell service area



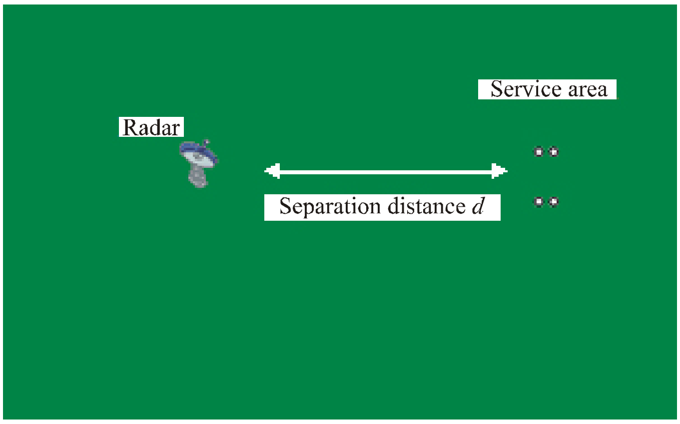
Rap 2112-05

5.3 Pico cell deployments

Interference from a pico-cell deployment could be modelled in many different configurations. The most basic configuration is a moderate sized, single floor building. From this basic configuration the modelling could increase to a multiple floor building and multiple buildings. A pico cell deployment would typically be small and limited to business areas. It is unlikely that an ARS or meteorological radar would be deployed within such a pico cell. For this reason modelling with the radar offset from the pico cell area was conducted. A pico cell is defined in this study to have average cell radius of 40 m as outlined in Report ITU-R M.2039. In this study, a pico cell coverage area of 1 km × 1 km was established. Four pico cell base stations were included in the coverage area. The simulation was run with the radar placed at the edge of the pico cell coverage area. Subsequent runs of the simulation varied the distance between the radar and the pico cell area (Fig. 6). In the analysis it is assumed that one IMT base station transmitter emission for each cell is co-channel with the radar receiver. Since the deployment scenario was in a building a pico cell base station antenna height of 10 m was used for the simulation.

FIGURE 6

Radar is offset from Pico cell service area



Rap 2112-06

Appendix 2
to Annex 1

Results of IMT sharing studies with air surveillance Type A, Type B and Type C radars within the 2 700-2 900 MHz band

1 Air surveillance radars

The ASR’s use continuous wave (CW) pulses and frequency modulated (chirped) pulses. The 2 700-2 900 MHz band is viewed as the optimum band for ATC radars used for air surveillance due to the strong balance between propagation characteristics and equipment size.

Only parabolic reflector-type antennas are used on radars operating in the 2 700-2 900 MHz band. The ATC radars have a cosecant-squared elevation pattern with a scan type of 360° in the horizontal plane. Newer generation radars use reflector-type antennas. Dual horns are used for transmit and receive to improve detection in surface clutter and can reduce the level of interference. The typical antenna height for the ATC radars is 8 m above the ground. The characteristics of various types of ATC radars (A, B, and C) used in these studies can be found in Table 5 of Appendix 1 to Annex 1. These radars perform air surveillance for terminal approach control and operate in a full 360° sector on a 24 h per day schedule. Radars A through C are typically located at all airports. Radars A and B are the current generation of radars while radar C is representative of the next generation system, which should augment and/or replace radars A and B after the year 2010. Radar D is a transportable system used for ATC at airfields where there are no existing facilities. When in use, radar D is operated 24 h a day. Since Type A and Type C radar specifications are similar, Type A separation distances were applied to the Type C radar. Consequently, simulations were only run on Type A and Type B radars.

2 Interference to air surveillance radars from IMT systems

2.1 Type A and Type B Air surveillance offset from a macro network

Figure 7 illustrates what effect increases in separation distances between an IMT macro cell service area and a Type-B ASR has upon *I*/*N* protection criteria. The results represent the output of a simulation where the air surveillance radar was offset from a CDMA-2000 3X network that consisted of base stations that were laid out in a regular grid pattern as shown in Fig. 4.

As shown in Fig. 7, an acceptable *I*/*N* value (< –10 dB) for the macro cell topology was reached when the radar was 595 km away from the IMT network. The effect of the terrain can be seen over a distance of 10-200 km away from the IMT macro cell service area.

FIGURE 7

Type B ASR-IMT macro network separation distances (km)

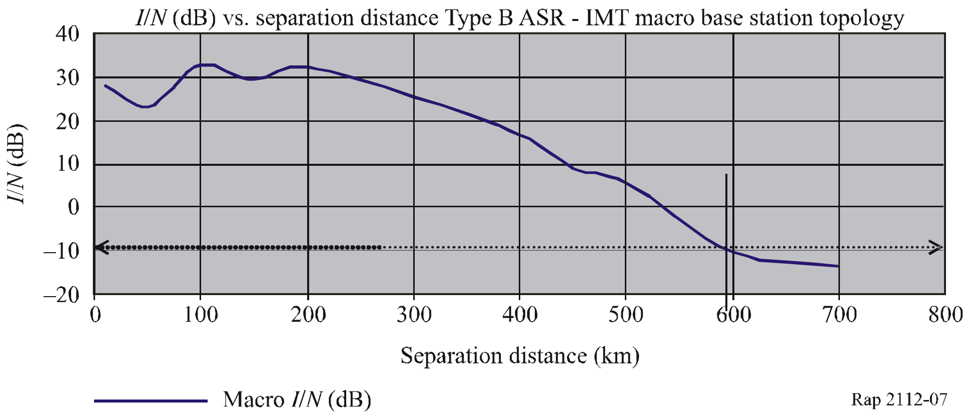
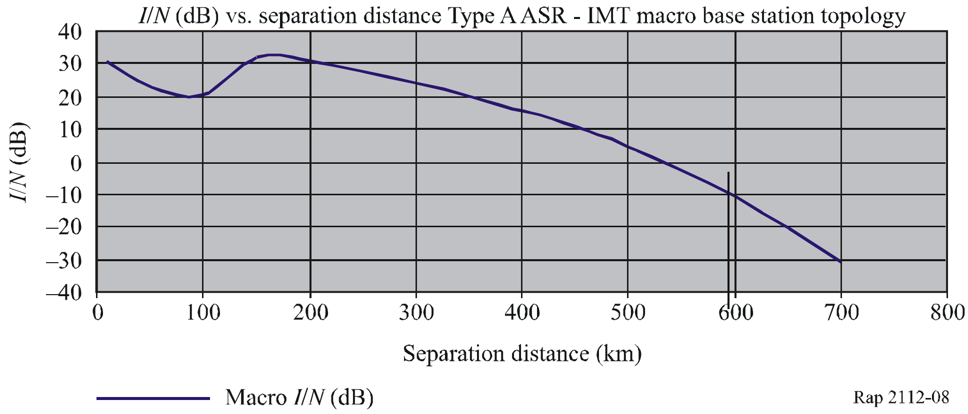


Figure 8 shows similar separation distances are required for Type A air surveillance radars.

FIGURE 8

Type A ASR-IMT macro network separation distances (km)



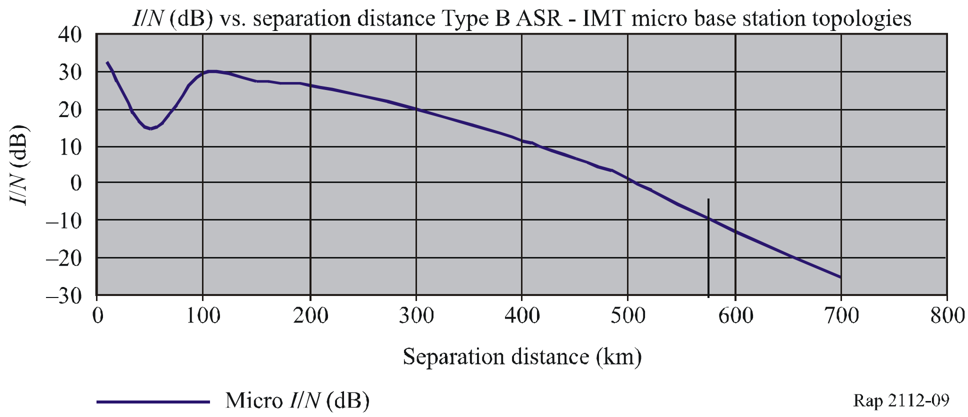
2.2 Type B air surveillance radars offset from a micro network

Figure 9 illustrates what effect increases in separation distances between an IMT micro cell service area and a Type-B ASR has upon *I*/*N* protection criteria. The results represent the output of a simulation where the air surveillance radar was offset from a CDMA-2000 3X network that was made up of base stations that were laid out in a regular grid pattern as shown in Fig. 5.

As can be seen in Fig. 9, an acceptable *I*/*N* value (< –10 dB) for the micro cell topology was reached when the radar was 575 km away from the IMT network. The effect of the terrain can be seen over a distance of 10-200 km away from the IMT micro cell service area.

FIGURE 9

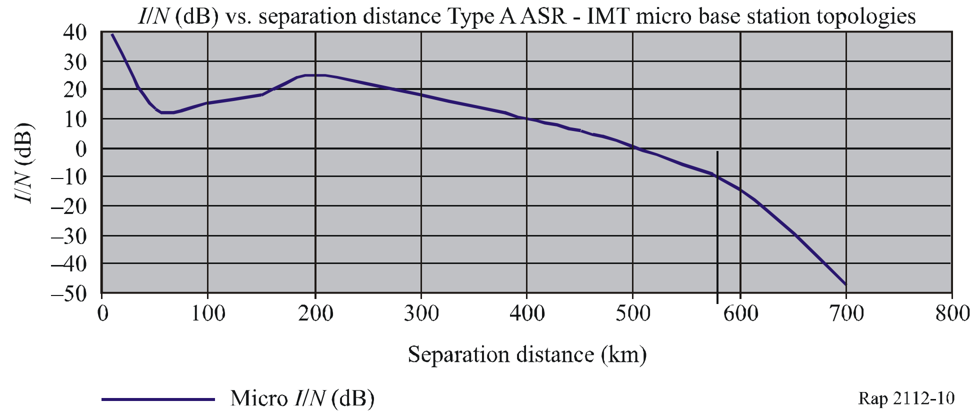
Type B ASR-IMT micro network separation distances (km)



As can be seen in Fig. 10, similar separation distances are required for Type A air surveillance radars.

FIGURE 10

Type A ASR-IMT micro network separation distances (km)



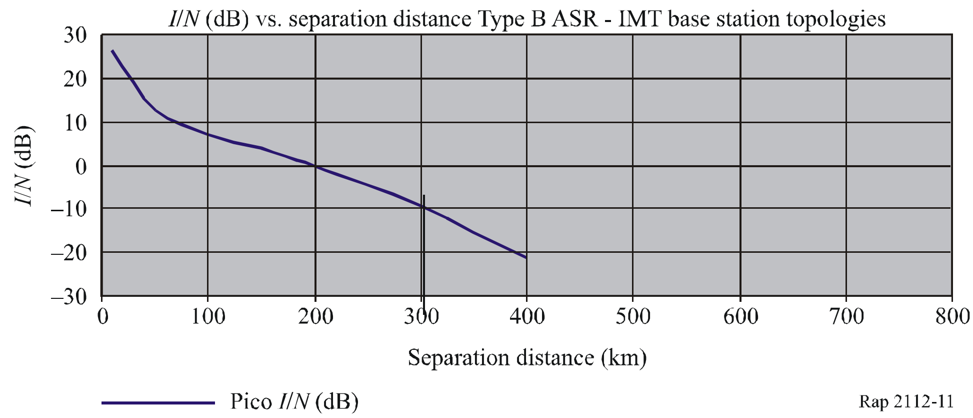
2.3 Type B air surveillance radar offset from a basic pico cell network

A basic pico cell network was modelled where a single floor building was serviced with a network of 4 base stations. The cell radius was set at 30 m. For the base station to radar interference case, the assumption was made that each cell can have one base station operating co-channel with the radar. Since the deployment scenario was within a building (accounting for 0-20 dB distribution for building penetration loss), a pico cell base station antenna height of 10 m was used for the simulation. Due to the small geographic area associated with pico cell deployment, a smooth earth model was used for this simulation.

Figure 11 illustrates what effect the increase in separation distances between an IMT pico cell service area and a Type-B air surveillance radar has upon *I*/*N* protection criteria. The results represent the output of a simulation where the air surveillance radar was offset from a CDMA-2000 3X network that was made up of base stations that were laid out in a regular grid pattern as shown in Fig. 6. As can be seen in Fig. 11, an acceptable *I*/*N* value (< –10 dB) for the micro cell topology was reached when the radar was 300 km away from the IMT network.

FIGURE 11

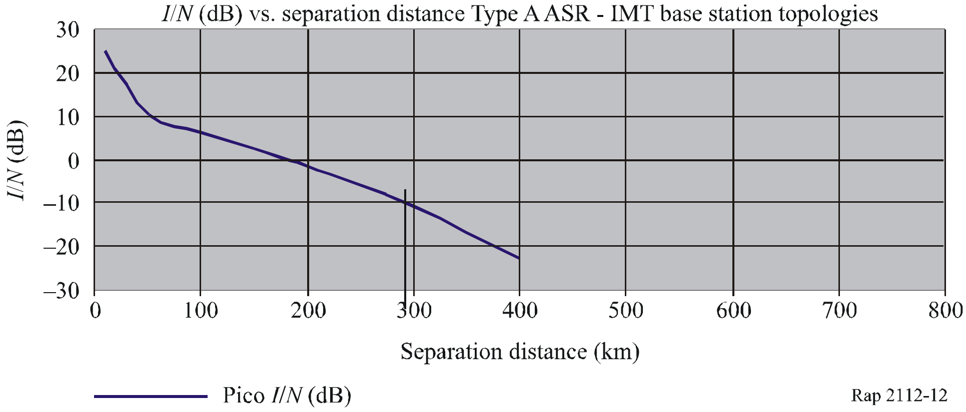
Type B ASR-IMT pico network separation distances (km)



As can be seen in Fig. 12, similar separation distances are required for Type A air surveillance radars.

FIGURE 12

Type B ASR-IMT pico network separation distances (km)



3 Discussion of results

The results of these simulations show that even with separation distances in excess of 500 km, the ASR *I/N* protection criteria for both Type A and Type B air surveillance radars, as defined by the ITU, cannot be met. These studies have also shown that interference from IMT systems to ASR's will impair the operation of incumbent radar systems when co-shared with IMT macro, micro and pico cell based topologies within the 2 700-2 900 MHz band. The required separation distances up to several hundred kilometers for sharing of the band preclude the co-channel deployment of IMT systems and radars.

The overall results of the study have shown that sharing of the 2 700-2 900 MHz band between Type A and Type B air surveillance radars and IMT systems is not feasible.

Appendix 3
to Annex 1

Results of IMT co-frequency compatibility studies with meteorological (Type G) radar within the 2 700-2 900 MHz band

1 Meteorological radars

Both meteorological and ASR's employ CW and frequency modulated (chirped) pulses within the band 2 700-2 900 MHz. Many weather radars employ Doppler technology allowing measurement of storm movement in addition to measurement of precipitation conventional radars provide. By utilizing Doppler radar technology, speed and direction of motion can be calculated while tracking severe weather storms such as tornadoes, hurricanes, and violent thunderstorms. As with ATC radars, weather radars have parabolic reflector-type antennas, which scan 360° in the horizontal plane. Weather radars are typically installed with an antenna height of 30 m above the ground.

Meteorological radars were developed for high spectral efficiency and exhibit very good transmitter emission characteristics and receiver selectivity characteristics. Reduction in transmitter or receiver bandwidth is not feasible without significant degradation of radar performance.

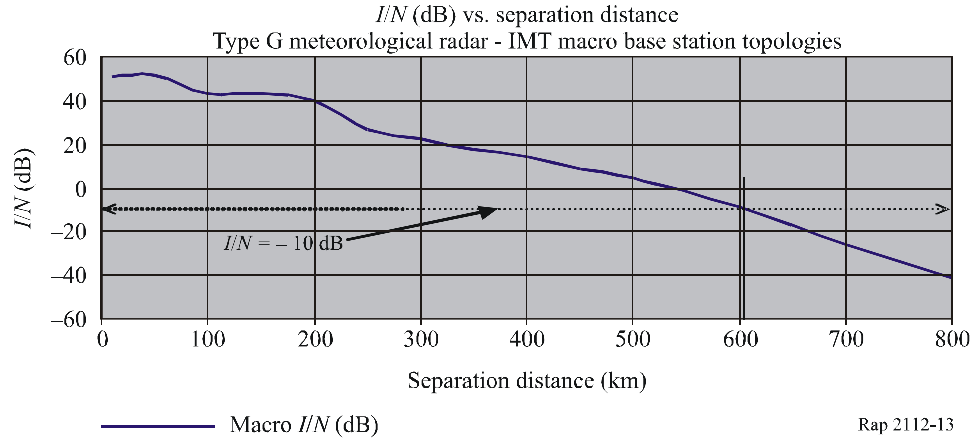
1.1 Meteorological radar offset from an IMT macro network

Figure 13 illustrates what effect the increase in separation distances between an IMT macro cell service area and a Type-G meteorological radar has upon *I*/*N* protection criteria. The results represent the output of a simulation where the meteorological radar was offset from a CDMA-2000 3X network that was made up of base stations that were laid out in a regular grid pattern as shown in Fig. 5.

As can be seen in Fig. 13, an acceptable *I*/*N* value (< –10 dB) for the macro cell topology was reached when the radar was 610 km away from the IMT network. The effect of the terrain can be seen over a distance of 10-200 km away from the IMT macro cell service area. This simulation shows similar results which could be attributed to Type G radar’s characteristic beamwidth and receiver’s bandwidth, however, a closer analysis of the results may need to be conducted.

FIGURE 13

Type G meteorological radar-IMT macro network separation distances (km)



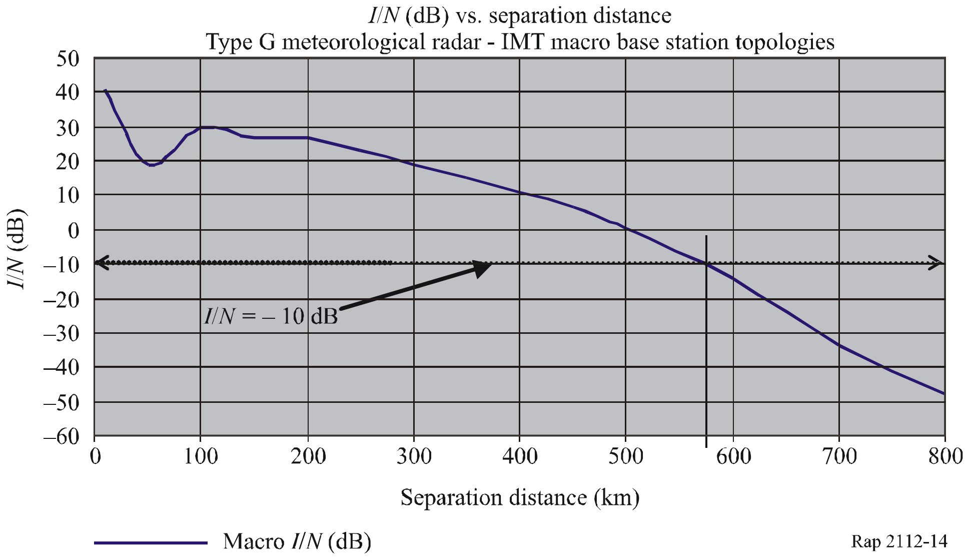
2 Meteorological radar offset from an IMT micro network

Figure 14 illustrates what effect the increase in separation distances between an IMT micro cell service area and a Type-G meteorological radar has upon *I*/*N* protection criteria. The results represent the output of a simulation where the meteorological radar was offset from a CDMA-2000 3X network that was made up of base stations that were laid out in a regular grid pattern as shown in Fig. 5.

As can be seen in Fig. 13, an acceptable *I*/*N* value (< –10 dB) for the micro cell topology was reached when the radar was 600 km away from the IMT network. The effect of the terrain can be seen over a distance of 10-200 km away from the IMT macro cell service area.

FIGURE 14

Type G meteorological radar-IMT micro network separation distances (km)



3 Meteorological radar offset from a basic pico cell network

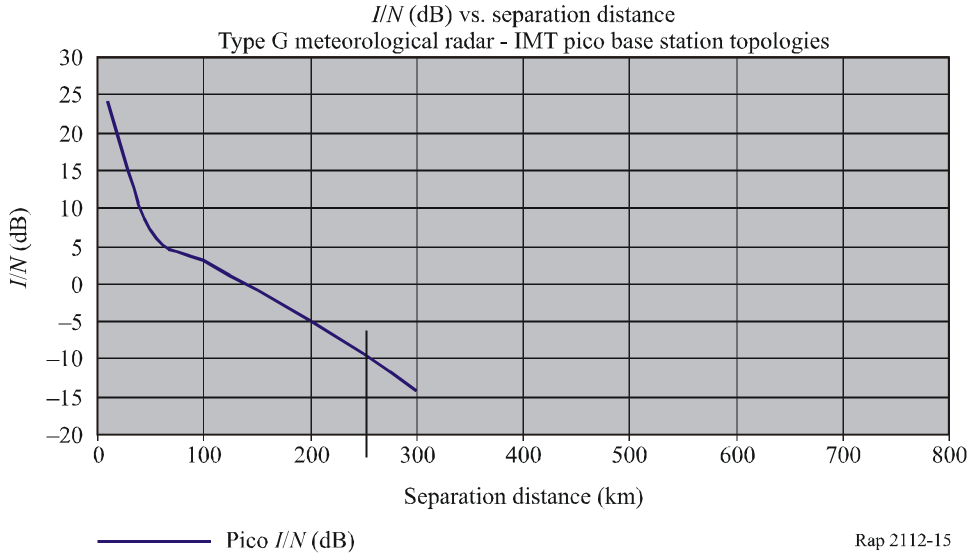
A basic pico cell network was modelled where a single floor building was serviced with a network of 4 base stations. The cell radius was set at 30 m. For the base station to radar interference case, the assumption was made that each cell can have one base station operating co-channel with the radar. Since the deployment scenario was within a building a pico cell base station antenna height of 10 m was used for the simulation. Due to the small geography that is associated with pico cell deployment a smooth earth model was used for those simulations

Figure 15 illustrates what effect the increase in separation distances between an IMT pico cell service area and a Type-G meteorological radar has upon *I*/*N* protection criteria. The results represent the output of a simulation where the air surveillance radar was offset from a CDMA-2000 3X network that was made up of base stations that were laid out in a regular grid pattern as shown in Fig. 6.

As can be seen in Fig. 15, an acceptable *I*/*N* value (< –10 dB) for the pico cell topology was reached when the radar was 250 km away from the IMT network.

FIGURE 15

Type G meteorological radar-IMT pico network separation distances (km)



4 Discussion of results

The results of these simulations show that, even with separation distances in excess of 500 km, the meteorological radar *I*/*N* protection criteria as defined by the ITU cannot be met. As such, the separation distances required for sharing of the band preclude the effective deployment of IMT systems. Even if such distances could be tolerated, regions in which sharing could take place would be severely limited due to the wide spread geographical deployment of ASR, meteorological, and other radar systems.

These studies have also shown that interference from IMT systems to meteorological radars will impair the operation of incumbent radar systems when co-shared with IMT macro, micro and pico based topologies within the 2 700-2 900 MHz band. The overall results of the study show that co-channel sharing of the 2 700-2 900 MHz band with IMT systems is not feasible.

Appendix 4
to Annex 1

Impact of air surveillance radars and meteorological radar operations upon IMT systems within the 2 700-2 900 MHz band

1 IMT as victim system

The interference originating from radars has different characteristics compared to that originating from an IMT network, which is necessary to take into account to obtain a complete assessment of the damage done by this type of interference.

To begin with, the antenna of the radar is rotating. This results in interference that is varying with time. This aspect has been included in the analysis, and will affect the time that the interference criterion for a particular device is, since the antenna beam of the radar is highly directional. Furthermore, the radar power is very high. As a result, there will be some level of interference to a co-channel IMT receiver even for large separation distances when the radar is transmitting. This feature is also reflected in the simulations.

Radar interference in this band is intermittent which is not included in this analysis. The analysis describes the probability of being interfered when the radar is active. The current simulation analyzes the interference effects during the period when the radar is active and does not take into account the interference effects during the time the radar does not transmit. IMT systems incorporate error correcting features such as coding and interleaving, which have not been included in this analysis. Although the analysis provides valuable information regarding the separation distances required to meet the IMT protection criteria limits for which some level of interference is present in the IMT network, it does not include an analysis regarding the quality of service degradation interference from a single radar into IMT network.

The potential for interference from radars into IMT systems was evaluated by using the radar characteristics from Recommendation ITU-R M.1464 and monitoring the interference levels at IMT stations. The simulation ran for one hour with a time step interval of 0.1 s.

1.1 Macro, micro and pico cell deployments

The interference criteria for the systems in the macro, micro and pico cell deployments are all approximately equal. The criteria are different for each of the radio interfaces. The required separation distance was determined establishing a line of IMT-2000 test points along a radial extending out from the radar location. The first test point was located 55 km from the radar. The remaining 19 test points were placed at a spacing of 30 km each. Using a cumulative distribution function in relation to the IMT *I*/*N* interference protection criteria, the simulation was run recording the amount of time each test point experienced interference levels exceeding the interference criteria in Table 5. Tables 6 and 7 provide the simulation results for the air surveillance radar into the IMT-2000 base stations and mobile respectively. The simulation was run with Recommendation ITU-R P.452 enabled with 0.001%. It should be noted that the result do not account for the radar duty factor. Meteorological radars typically transmit multiple waveforms which can cause multiple interferences on frequent basis especially when these type of radars monitor fronts and the antenna remains stationary for a period of time. In the cases where 100% interference is shown in the tables below, the interference will occur at a maximum of 5 min/year due to the 0.001% required time percentage for which the calculated basic transmission loss is not exceeded when applying Recommendation ITU-R P.452 in the simulation model.

TABLE 6

Summary of interference from the air surveillance radar into IMT-2000 base stations

Test point	Separation distance (km)	% time CDMA-2000 1X	% time CDMA-2000 3X	% time UWC-136 30 kHz	% time UWC-136 200 kHz	% time TD-CDMA
1	55	100.0	100.0	100.0	100.0	100.0
2	85	100.0	42.60	100.0	100.0	100.0
3	115	20.00	17.72	100.0	100.0	100.0
4	145	16.58	14.84	100.0	100.0	100.0
5	175	13.72	12.44	100.0	100.0	22.20
6	205	11.31	9.91	42.21	43.38	23.37
7	235	9.11	6.75	19.30	19.68	15.96
8	265	5.79	4.73	15.98	16.26	14.05
9	295	5.22	4.33	13.41	13.58	11.96
10	325	3.56	2.75	10.68	10.80	9.59
11	355	2.40	1.94	8.29	8.35	6.54
12	385	1.42	1.11	5.41	5.57	4.61
13	415	0.82	0.68	3.67	3.69	2.89
14	445	0.60	0.33	2.71	2.79	2.12
15	475	0.26	0.14	1.00	1.00	0.75
16	505	0.08	0.05	0.64	0.64	0.51
17	535	0.04	0.04	0.42	0.42	0.35
18	555	0.00	0.00	0.07	0.07	0.06
19	585	0.00	0.00	0.02	0.01	0.01
20	615	0.00	0.00	0.10	0.10	0.08

TABLE 7

Summary of interference from the air surveillance radar into IMT-2000 mobile stations

Test point	Separation distance (km)	% time CDMA-2000 1X	% time CDMA-2000 3X	% time TD-CDMA
1	55	14.48	12.93	51.23
2	85	10.79	9.58	20.63
3	115	9.05	6.80	15.15
4	145	4.96	3.89	12.27
5	175	4.29	3.50	9.00
6	205	2.93	2.43	8.55
7	235	2.07	1.65	5.26
8	265	1.25	0.94	3.73
9	295	1.04	0.78	3.28
10	325	0.53	0.37	2.05
11	355	0.30	0.25	1.35
12	385	0.08	0.03	0.80
13	415	0.07	0.03	0.39
14	445	0.01	0.00	0.19
15	475	0.00	0.00	0.05
16	505	0.00	0.00	0.04
17	535	0.00	0.00	0.00
18	555	0.00	0.00	0.00
19	585	0.00	0.00	0.01
20	615	0.00	0.00	0.00

1.2 Interference from multiple radars into IMT-2000

As stated in Appendix 2 and Appendix 3 to Annex 1, the simulation results show that co-channel operation interference can occur even with large separation distances between ASR and meteorological radars and an IMT mobile or base station.

This analysis examines the case of multiple interference sources to both IMT-2000 base stations and mobiles. The radars considered were Radar C (air surveillance radar) and Radar G (meteorological radar) from Recommendation ITU-R M.1464. Simulations were run with the radars operating at the appropriate angular rate of rotation and pulse repetition frequency (PRF). Pulse widths used were 5 μs for radar G and 100 μs for radar C with PRF of 500 Hz and 1 kHz respectively. The pulse widths and PRFs used are approximations of the actual system characteristics and were used due to practical considerations of the simulation program. With the exception of pulse width and pulse repetition rate, all of the other radar and IMT system characteristics that were used in this simulation can be found in Tables 8 and9.

TABLE 8

Characteristics of IMT-2000 mobile stations and base stations

Receiver type	Base station	Mobile
Antenna height (m)	30	1.5
Antenna gain (dBi)	18	0
Transmit power (W)	20	0.125
Receiver noise figure (dB)	5	9
Receiver noise level (dB(W/MHz))	–139	–135

TABLE 9

Radar characteristics
(Recommendation ITU-R M.1464)

	Radar C	**Radar G**
Antenna rotation rate (degrees/s)	75	18
Transmitter power (dBW)	44	57
Antenna main beam gain (dBi)	34	45.7
Antenna height (m)	8	30
Pulse width	89	4.7
Pulse repetition rate	1 050	452

The antenna patterns that were used in this simulation can be found in Figs. 16 and 17.

FIGURE 16

Plot of meteorological radar (Radar G) antenna pattern used in analysis

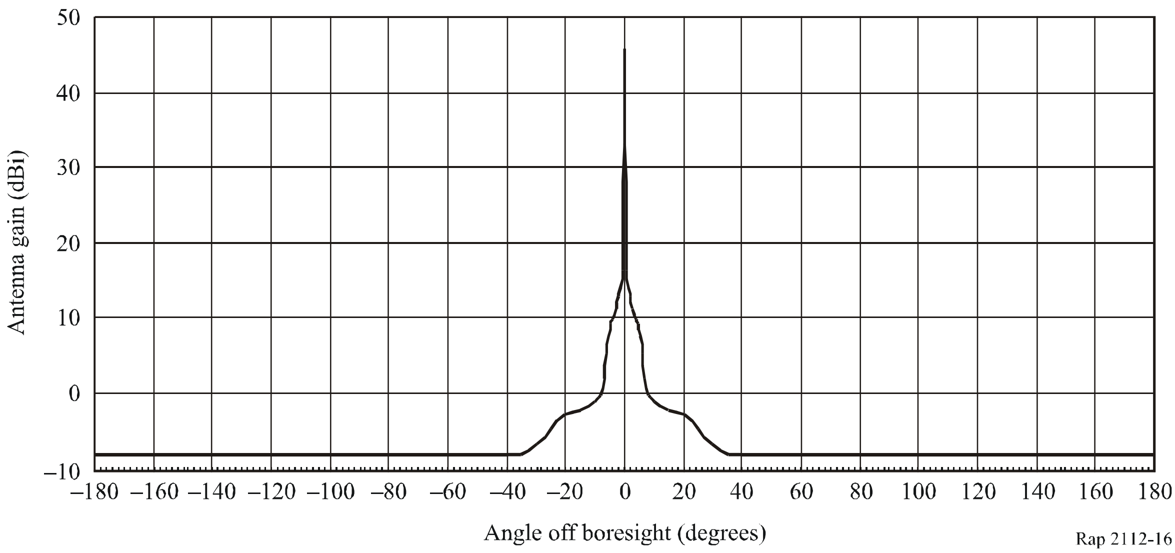
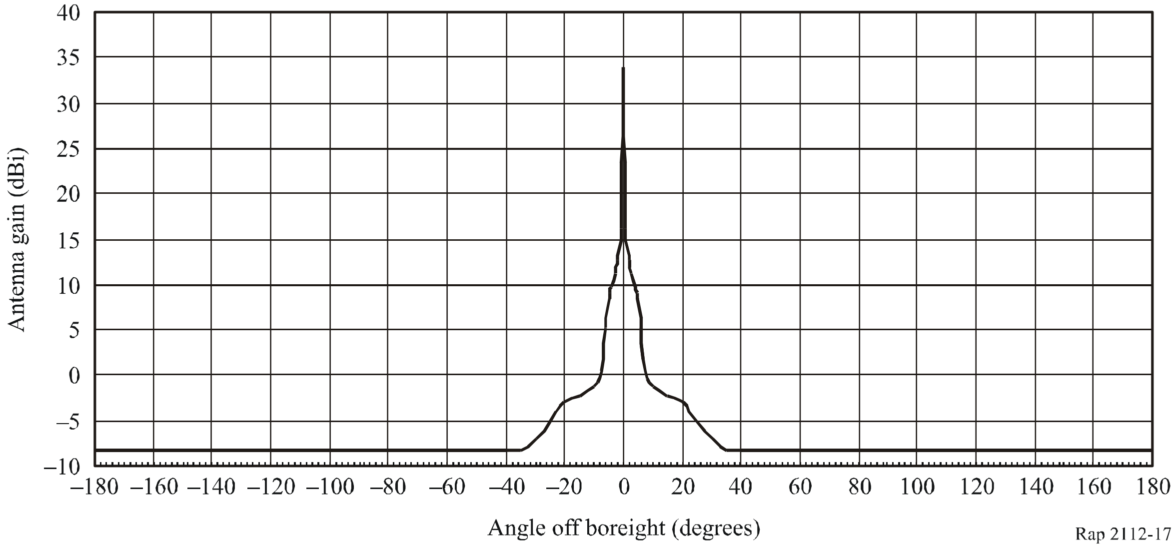


FIGURE 17

Plot of air surveillance radar (Radar C) antenna pattern used in analysis

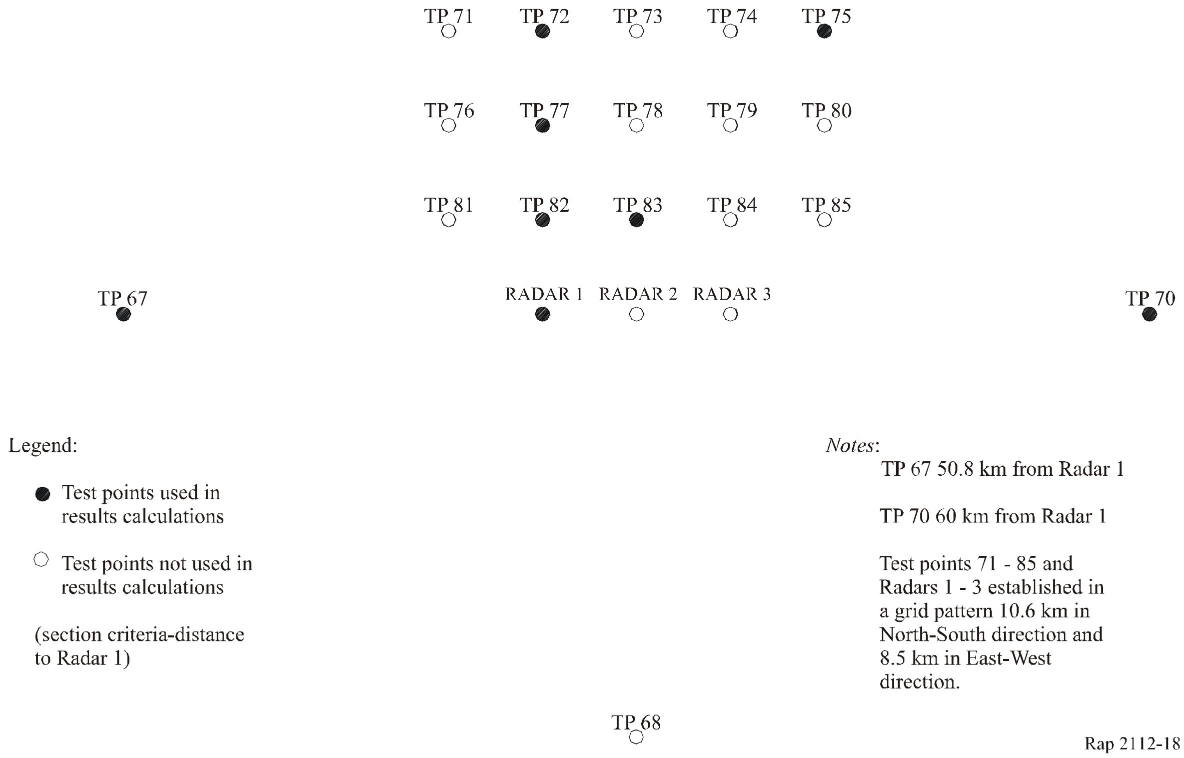


All simulations were run in both a single radar configuration and a three-radar configuration. The three-radar configuration used three radars spaced at eight kilometres illuminating IMT-2000 receivers at distances ranging from 10-150 km from these radars. The initial azimuths of the radars were 0°, 90° and 180° and pulse timing was offset by several pulse widths. Therefore, the antennas and transmitted pulses were not aligned at the start of the simulation in order to avoid worst-case conditions. In all cases the IMT-2000 network was set up as receive only and co-channel with the radar at 2 800 MHz. The propagation model used was Recommendation ITU-R-P.452 configured for climate zone A2 (inland). Ducting and troposcatter were enabled. Ducting can occur but is typically not a major contributor to propagation in climate zone A2. Nevertheless, it was included for completeness.

A three radar configuration was chosen as a "typical" situation but in many urban and suburban areas it is far from worst case. For example, an NTIA spectrum survey of the Los Angeles, CA. area (NTIA Report 97-336) shows eleven radars operating in the 2 700-2 900 MHz band with peak power ranging from –5 dBm to –20 dBm when measured at a test point located 40 km north west of the city. Twenty-six test points were set up as IMT-2000 receivers as shown in Fig. 18. The simulations were run once with the receivers set up as base stations for both the one radar and three radar configurations. The simulations were then repeated with the receivers set up as mobile stations for both the one radar and three radar configurations.

FIGURE 18

Simulation system configuration



Simulation results data

The results of the simulation can be found in Tables 10, 11, 12 and 13. The three-radar configuration did not produce significantly different results from the single radar configuration due to the offset in azimuth and pulse timing preventing any overlap in the respective pulses at the peak antenna gains. Consequently, the analysis that follows is based only on the single radar data using radar one as the interference source. Additional analysis is needed to show the interference affects multiple radars have on IMT systems taking into account the increased effective PRF compounding the length of interference time that would be seen at the IMT receiver's LNA.

TABLE 10

Simulation results of Radar G interference to IMT-2000 base stations

Test point	Distance to Radar 1 (km)	1 Radar Worst I (dBW)	Mean I (dBW) (std dev)
82	10.6	–3.0	–52.5 (5.9)
83	13.5	–4.5	–54.6 (5.9)
77	21	–5.4	–58.5 (5.9)
72	32	–14.2	–62.2 (5.9)
75	41.3	–18.4	–64.5 (5.8)
67	50.8	–19.2	–67.5 (4.5)
70	60	–36.0	–88.5 (6.9)

TABLE 11

Simulation results of Radar G interference to IMT-2000 mobile stations

Test point	Distance to Radar 1 (km)	1 Radar Worst I (dBW) Mean I (dBW) (std dev)	
82	10.6	–22.7	–71.7 (4.4)
83	13.5	–24.5	–73.5 (4.8)
77	21	–27.3	–77.6 (4.5)
72	32	–31.5	–81.3 (4.5)
75	41.3	–35	–116 (7.3)
67	50.8	–40	–126 (9)
70	60	–49	–135 (10.8)

TABLE 12

Simulation results of Radar C interference to IMT-2000 base stations

Test point	Distance to Radar 1 (km)	1 Radar Worst I (dBW) Mean I (dBW) (std dev)	
82	10.6	–24.7	–78.3 (4.7)
83	13.5	–26.7	–80.3 (4.7)
77	21	–29.3	–84.3 (4.7)
72	32	–33	–88 (4.7)
75	41.3	–39	–108 (5.8)
67	50.8	–46.5	–119 (6.6)
70	60	–40.3	–128 (7.9)

TABLE 13

Simulation results of Radar C interference to IMT-2000 mobile stations

Test point	Distance to Radar 1 (km)	1 Radar Worst I (dBW) Mean I (dBW) (std dev)	
82	10.6	–44	–96.3 (4.7)
83	13.5	–46.3	–98.3 (4.7)
77	21	–48.6	–131 (8.6)
72	32	–55.3	–144 (9.7)
75	41.3	–57.3	–154 (10.8)
67	50.8	–60.6	–162 (12)
70	60	–56	–166 (12.5)

A seven element subset of the test points was selected based on their approximate locations at 10, 13, 20, 30, 40, 50 and 60 km distances from the location of radar one. The worst I values represent the peak I recorded at each test point and are included as a basis to determine the potential for damage to the receiver front end and for worst case over load response.

The mean value and standard deviation of I, the number of radar pulses exceeding –55 dBW at the receiver antenna connector, and the number of radar pulses exceeding 25 dB above the noise floor at the receiver antenna connector were recorded for all single radar simulations.

2 Discussion of results – Interference from radars into IMT-2000 stations

During the radars' short active transmission states, the simulation results summarized in Tables 6 through 13 show that co-channel operation interference can occur at large separation distances between types A and C radars and an IMT-2000 or IMT-Advanced mobile or base station. However, the results do not take into account the affects of interference when the radar is not transmitting. In disabling and enabling the various propagation mechanisms within the propagation model, it was found that at closer distances line of sight and diffraction were the contributing propagation mechanisms, as expected. As the line-of-sight and diffraction losses increased significantly to protect the IMT-2000 station, ducting and troposcatter became the dominant propagation mechanisms. Operational experience supports these results where occurrences of bistatic coupling (forward scattering of the radar signal into another radar) are periodically noted between co-channel radars when the antenna rotations become synchronized. The radars experiencing the bistatic coupling can be separated by many hundreds of kilometres. The propagation for the larger distances in this analysis can be likened to the bistatic coupling experienced between radars.

3 Potential interference mechanisms

Interference from radar pulses has the potential to degrade IMT-2000 receiver performance via a number mechanisms including, but not limited to, power levels significantly above the receiver noise level, LNA overload, incorrect operation of the AGC, interference to signal ratios beyond the dynamic range of the analog to digital converter (ADC), filter overload, and mixer overload. A number of these interference mechanisms can produce responses that last long after the radar pulse has ended. Depending on the severity of the interference the effects can cause problems ranging from a reduction in Quality of Service to an inability to operate.

The analog sub-systems that come before (e.g. LNA, filters and mixers) and the digital sub systems that come after the ADC can saturate if the received signal is too strong. When these systems become saturated the overall performance of the receiver is degraded due to intermodulation and limiter effects. This can result in poor voice quality, dropped calls, inability to correctly process handovers and loss of service.

There is currently a lack of information on specific pulsed interference thresholds at which IMT-2000 and IMT-Advanced receivers are immune to the various interference mechanisms. In order to move this issue forward a number of assumptions have been made based on CDMA One and CDMA 2000 1X designs and current ITU texts.

4 AGC interference mechanisms

In general AGC is provided over the full dynamic range of the received signal power. In wireless environments a digital receiver often receives a signal that experiences rapid and wide variations in signal power due to channel fading and other causes (e.g. potential interference from other systems that operate within the band.). Problems arise when an AGC circuit is required to respond to a change in frequency, as seen during the processing of an inter-frequency handover, or to a high level step function in power. A typical AGC circuit contains a control loop and relies on filtering successive signal samples. As a result, it takes a certain time period for the AGC to settle. This time is known as the AGC settling time. System performance becomes degraded when the AGC settling time occupies a large percentage of the total switching time.

Accurate power estimation is required for proper operation of WCDMA systems. Incorrect estimation of the signal power can severely degrade performance of the AGC scaling and the operation of the despreading function. In severe cases timing and synchronization can be lost. Assuming that the power detection circuitry of the AGC has a fast time constant on the input (close to the chip time) and a longer time constant (greater than 10 μs) to facilitate average signal power estimation, it will respond fast enough to capture close to the peak of a radar interference and then decay over tens to hundreds of microseconds. Large radar pulses combined with long time constants in the AGC could render the system inoperable in cases where the power estimation has not recovered well within the duty cycle of the interfering radar. The impact will be dependent upon the AGC design and the selection of time constants. Interference problems could be mitigated by careful design of the receiver chain.

Exact values for the AGC time constant, power estimation sample rate, and required power estimation accuracy are needed to fully define the problem as it relates to IMT-2000 and IMT-Advanced systems. Initial analysis indicates that the occurrence of power overestimation could be a significant result of radar interference.

5 Filter and mixer interference mechanisms

While mixers can typically handle higher power levels than LNAs, both have self-resonance frequencies that could potentially be excited by high power radar pulses. The nonlinear response of mixers to over load can generate a large number of spurious signals or noise pulses that can be extended by tens of microseconds due to pulse spreading in the IF filters. This will again have the effect of increasing the effective duty cycle of the interfering signals and the resulting bit error rate (BER). Further study is required using actual device characteristics.

6 ADC interference mechanisms

The signal that is present at the input to the ADC consists of the desired signal, noise that is associated with the analog circuitry that precedes the ADC, and any interfering signals present at the receivers’ antenna. As shown in §§ 5, 6, and 7, the presence of a high power interfering signal at the input to an IMT receiver, rich in spectral content, (e.g. radar pulse) can overload the IMTs LNA drive its mixers into a non-linear mode of operation, and extend its AGC settling time. These results in degraded performance, poor voice quality, dropped calls, uncompleted handovers and, in some cases, total loss of service. The effect of strong pulses can also result in the saturation of the analog to digital converter.

Assuming future IMT-receivers will use 14 bit ADC, IMT systems will, at best, maintain the ability to resolve 84 dB of dynamic range (1 part in 214). In cases where the signal level interference is equal to or greater than the desired signal level, the desired signal will be undetectable. In cases where the ADC is saturated, the desired signals’ level will be below the resolution of the ADC and will be lost. In both cases an IMT system would be rendered inoperable.

Annex 2

Study B
Compatibility of airport surveillance radars and meteorological radar with IMT Systems within the 2 700-2 900 MHz band

Introduction

The band 2 700-2 900 MHz is allocated worldwide on a primary basis to aeronautical radionavigation radars (ARNS), including radars providing airport surveillance and air traffic control. In addition, meteorological radars are afforded equal status to the ARNS for operation in this band. Since ARNS radars perform a safety service as specified by RR No. 4.10, harmful interference must be avoided. Introduction of other services in this band must thus be studied very carefully, to ensure that interference is kept at acceptable levels so as not to compromise the quality of the radar services in those countries using this band for the ARNS and meteorological radars.

WMO records indicate that at least 320 meteorological radars in the 2 700-2 900 MHz band are currently in operation in more than 52 countries. While some administrations have low numbers of systems in operation, one must also remember that the use in neighbouring countries must be considered as well when determining the availability of spectrum by coordination in case large separation distances are required. Furthermore, future additional airport surveillance radars and meteorological radars may need to be considered.

However, the importance of additional spectrum for IMT has been recognized, and the band 2 700-2 900 MHz has a number of advantages for IMT:

– this band is near the bands already identified for IMT-2000, which may facilitate the use of some of the base and mobile station hardware as in the band 2 500-2 690 MHz and would present similar propagation conditions; it is adjacent to the IMT-2000 extension band 2 500-2 690 MHz simplifying development and manufacture of equipment resulting in economy of scale and thus has added benefits for the developing countries;

– the propagation characteristics are more favourable than for some other candidate bands, as suggested in the range 3-5 GHz.

Furthermore, the timing when IMT would be deployed in volumes in this band is expected to be somewhere between years 2 015-2 020, depending on market need and national consideration, so there is ample time to consider the coexistence situations for the appropriate coordination of the usages between countries.

1 Parameters of IMT-2000 and IMT-Advanced

The parameters used for the IMT-2000 have been obtained from Report ITU-R M.2039 (Table 1 contains a summary of these parameters). The ACLR parameters have been obtained from 3GPP 25.104 (3GPP TS 25.104, 3rd Generation Partnership Project: technical specification group radio, access network; base station radio transmission and reception (FDD)), and the channel spacing has been 5 MHz for IMT-2000. No feeder loss has been assumed for IMT-2000 systems. It should be noted here that the assumed micro BS power is unusually high. A more realistic value could have been 30 dBm, see also the micro cell power for IMT-Advanced below. Furthermore, feeder loss has not been included in the IMT-2000 figures.

TABLE 14

Power and antenna characteristics of IMT-2000 macro, micro and pico base stations

	Macro BS	Micro BS	Pico BS
Output power (dBm)	43	38	24
Antenna main beam gain (dBi)	17	5	0
Antenna height	30	5	1.5

The IMT-Advanced parameters for macro and micro base stations used are essentially those that have been submitted to ITU-R WP 8F for usage in the sharing studies, see Table15. Although the table is originally for 20-100 MHz bandwidth, a bandwidth of 10 MHz has been chosen for IMT-Advanced in this study. However, the output power has been set to the maximum allowed in Table 2, which with conservative assumptions about antenna gain and feeder loss (i.e. ensuring not to underestimate interference to radars) becomes 43 dBm for macro and 30 dBm for micro cells. Pico base station information has also been added, using partly information from Report ITU-R M.2039 adapted to IMT-Advanced and partly the same values as for macro and micro base stations. The result is a 24 dBm output power. The output power is given as effective isotropically-radiated power (e.i.r.p.) density range, with a maximum allowed transmitted power including antenna gains and feeder losses. The output power has been assumed to be at the maximum level for both IMT-2000 and IMT-Advanced throughout the simulations, i.e. without any decrease due to power control.

TABLE 15

Power and antenna characteristics of IMT-Advanced macro, micro and pico base stations

	Macro BS	Micro BS	Pico BS
e.i.r.p. density range, scaled to 1 MHz bandwidth	39-46 dBm/MHz	15-22 dBm/MHz	4-11 dBm/MHz
Antenna main beam gain (dBi)	20	5	0
Max trx power + antenna gain – feeder loss (dBm)	59	35	24
Antenna height (m)	30	5	1.5
ACLR, 1st adjacent (dB)	45	45	45
ACLR, 2nd adjacent (dB)	50	50	50

Inclusion of the effects of antenna tilting for IMT base stations would reduce the interference to the radar from IMT macro base stations. However, this has not been included in this study.

It should also be noted that in this study it is assumed that the IMT networks use these frequencies for downlink transmission only. This increases control of interference to a larger extent by network guidelines and planning. This can be managed by producing a Resolution in addition to the modification of the RR. The uplink traffic would have to be handled on a frequency in another band.

2 Aeronautical radionavigation and meteorological radar parameters

Information and characteristics for the radars were obtained from Recommendations ITU-R M.1461, ITU-R M.1464, ITU-R P.452 between stations on the surface of the Earth at frequencies above about 0.7 GHz. The antenna diagrams used are presented in Figs. 19 and 20. The meteorological radar antenna pattern is from the Federal Meteorological Handbook No. 11, Part B, § 3.28, worst case envelope. Assumptions regarding selectivity of the radars are discussed in § 5.3, describing the frequency dependent rejection between the two systems.

FIGURE 19

Plot of ARNS radar (Radar A) antenna pattern used in analysis

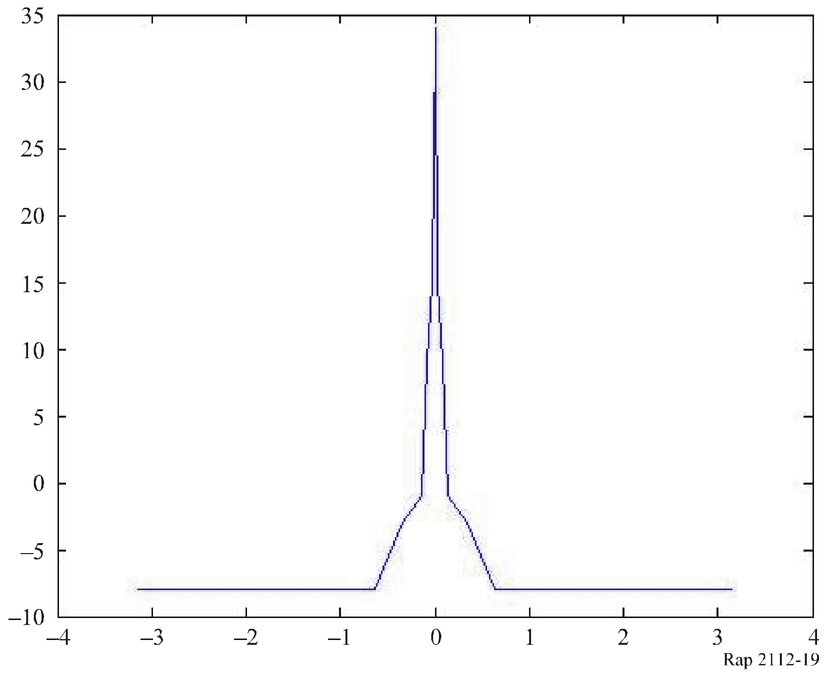
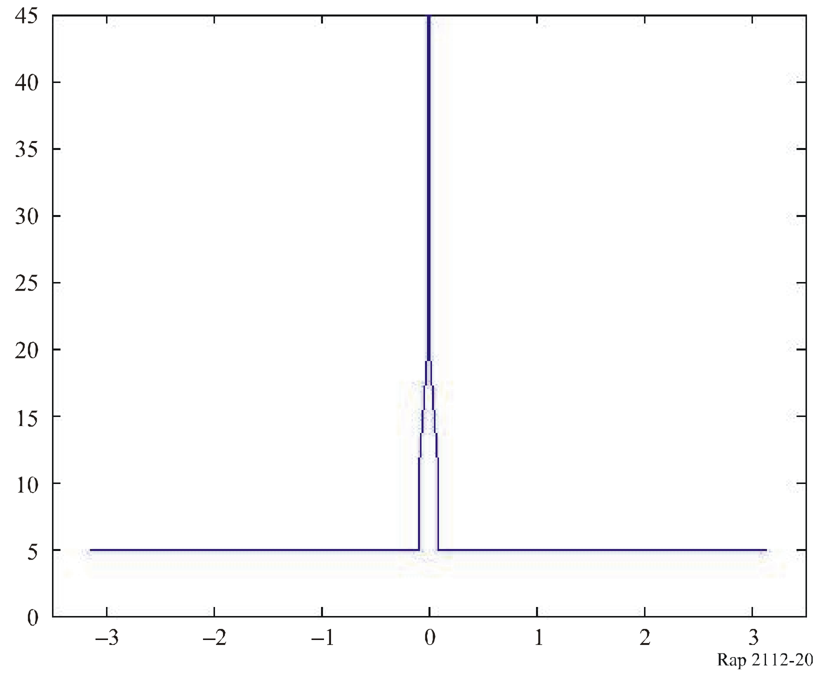


FIGURE 20

Plot of meteorological radar (Radar G) antenna pattern used in analysis



This text includes information on aeronautical radionavigation (type A-F) and meteorological (G and H) radars. Their relevant radar parameters for this study are summarized in Table16. The acceptable interference is calculated based on the knowledge of the noise level and the acceptable *I*/*N* ratio as described by Recommendations ITU-R M.1461 and ITU-R M.1646. The simulations were configured to closely approximate the operation of the radar. Antenna rotation was also included since it is one of the important IMT-to-radar interference aspects used in the analysis. Figure 21 shows how the interference to the radar from a macro cellular system varies as a function of the azimuthal angle of the radar antenna, from –180° to 180° for a scenario with a smooth earth, so as to display clearly the interaction between radar and IMT antenna directions. (The scenario is further described in § 6.) The absolute levels of interference of course depend on the actual separation distance between a radar station and the interfering IMT base station. This picture is only an example and is not used any further in the calculations of the required separation distances. Throughout the simulation analysis the angle (i.e. that for which the interference to the radar is highest) giving the highest interference has been presented for each scenario studied.

TABLE 16

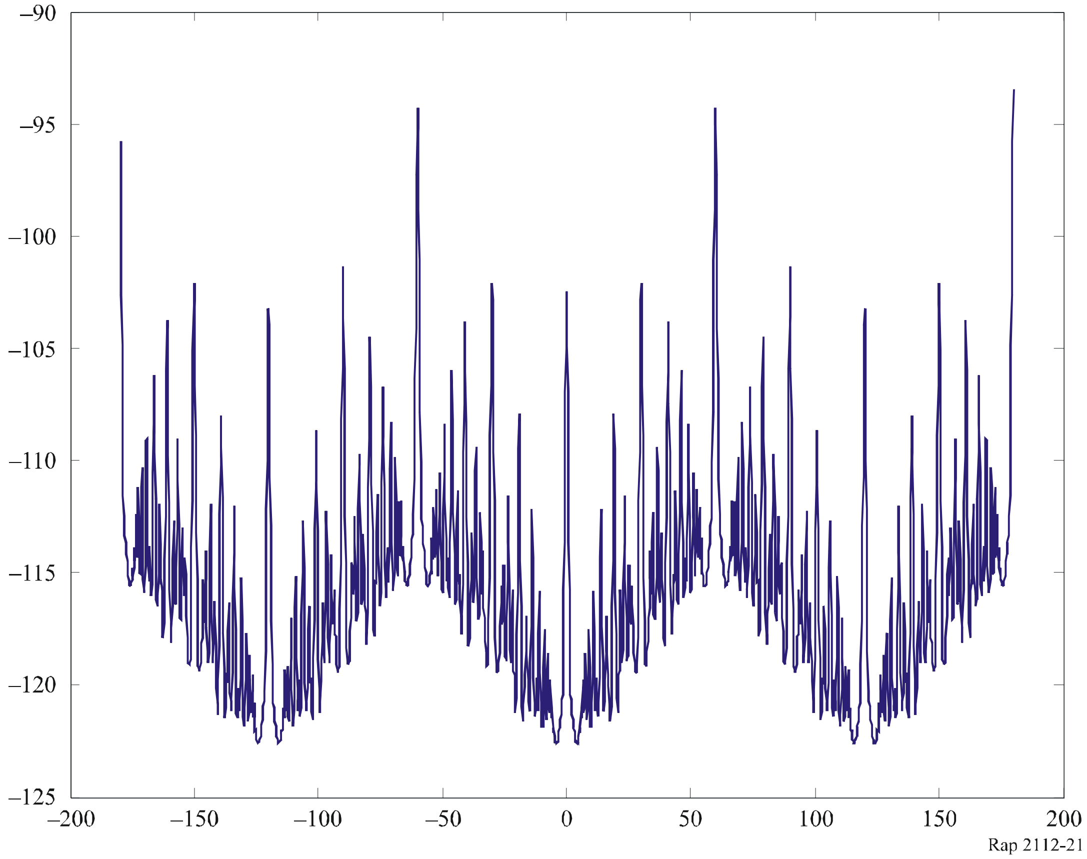
Basic characteristics of radars considered

Radar type	**Iacc (dBm)**	**Gr (dBi)**	**Antenna azimuthal beamwidth**	**Receiver (IF) bandwidth**
A	–113	33,5	1,35	5 MHz
B	–121,9	33,5	1,3	653 kHz
C	–108,9	34	1,45	15 MHz
E	–121,1	34,3	1,4	1,2 MHz
F	–116	33,5	1,5	4 MHz
G	–123,9	45,7	0,92	630 kHz
H	–121	38	2	0,25/0,5 MHz

The highest acceptable level of interference, Iacc, is defined by $I/N = -10$ dB, where *N* is the radar receiver noise, see Table 16. An antenna height of 8 m is used for radar type A-F, and 30 m radar for type G-H. It is assumed that there is no loss in antenna gain due to antenna tilt for the radar stations in the simulations, since radars are often operating at very low elevation angles.

FIGURE 21

An example of interference perceived by the radar (Type A) from a hexagonal macro cellular system as a function of the azimuthal angle of the radar antenna



In the analysis, we have mainly focused on radar stations of types A and G. It can be assumed that interference to other types of radars can be related to that experienced by A and G, by adjusting for bandwidth, antenna gain and azimuthal beamwidth. Note that it is of great importance to consider some additional aspects regarding radar when considering co-existence with IMT networks.

The rotation of the radar means that interfered IMT receivers may only be subjected to strong interference occasionally, when the radar antenna main beam is directed towards it. Due to the narrow beam width, this happens only for a very small fraction time of every rotation. It should be noted however that due to the high power of the radar, IMT receivers less distant from the radar may experience interference even when they are not within the main beam.

The radar pulses are very short in time, roughly 1-100 µs, and have pulse repetition rates (PRR) of about 1 kHz or lower. The duty cycle is thus in the order of a few percent in most cases. Even for the more difficult cases such as radar C (see Recommendation ITU-R M.1464), a radar with long pulses and PRR 1 kHz, it is not more than roughly 10%. Cellular systems, such as IMT, are built to function in the presence of inter system interference, and have error correcting features (coding, interleaving), and it is thus not sufficient to consider only interference levels in relation to noise levels, or to look at maximum interference levels. This will be explored further in the section on radar interference to IMT terminals.

Interference effects to the radar cannot be averaged over an entire radar rotation. Radar results must be accurate for every direction and for every distance (in all so-called "cells"), and it is thus not acceptable to trade high interference in one direction for low interference in another by an averaging process.

3 Interference criteria of the systems

The radar interference calculation methodology and protection criteria are referenced from Recommendations ITU-R M.1461 and ITU-R M.1464. See also § 3. The results are listed in § 3.2. For protection criteria for IMT networks, see § 5.2.

4 Propagation model

The IMT propagation model that has been used in this study is Recommendation ITU-R P.452, together with terrain data based on a circular area, radius 250 km, around a point in south western France (45° 40'13" N, 02° 07'47" E). The water density of the air is assumed to be 3g/m3. The frequency used in the calculations is 2.8 GHz. As for clutter protection, the method recommended by 3M has been used, which is described in Appendix 1 to Annex 2. (It should be noted that this method is more recent than the one currently in Recommendation ITU-R P.452).

The required *I*/*N* value for the radar stations is assumed to be a so-called short-term interference value, i.e. it should be only exceeded for a small percentage of the time. Although there is no information in Recommendations ITU-R M.1464 or ITU-R M.1461 regarding this percentage value, 0.001% has been chosen as a conservative estimate. This corresponds to roughly 5 min per year.

The methodology for using Recommendation ITU-R P.452 for short-term interference is described in Recommendation ITU-R SF.1006, and can be further clarified as follows:

When multiple potentially-interfering signals are combined at a victim receiver, the principles outlined in Recommendation ITU-R SF.1006 in introducing equations (3) and (4) are appropriate. These principles, when used in conjunction with Recommendation ITU-R P.452, can be stated more fully as follows.

For the short-term criterion (signals exceeded for a percentage time typically in the range 1% to 0.001%, as appropriate) for each unwanted signal use Recommendation ITU-R P.452 iteratively to find the percentage time for which the maximum permissible interference level (for the short-term criterion) is exceeded. Sum these times for all unwanted signals. If the resulting aggregate time exceeds the short-term criterion, then harmful interference should be assumed.

The above procedure for the short-term interference can result in Recommendation ITU-R P.452 being used for percentage times less than its normal minimum of 0.001%. In fact, the model has been tested down to 0.000001%. The predicted signal-level enhancements tend to flatten out (i.e. do not greatly increase) for such extreme times, and measurements have recently shown that this appears to be realistic. It should be noted that the short-term interference is based on the assumption that interferers are anti-correlated in terms of short-term propagation.

As mentioned above, the radar functionality must be guaranteed for all directions. Consequently it should be guaranteed for every direction that the interference does not exceed the radar interference criterion ($I/N > -10$ dB) for more than 0.001% of the time as assumed for the calculations with the Recommendation ITU-R P.452 model. This is the methodology used in the simulations; even for the direction experiencing the worst interference the short-term interference criterion must not be exceeded.

In summary, an upper bound for the interference time for each base station (given the acceptable interference for a particular type of radar) is calculated by decreasing the percentage parameter in the propagation calculation until the interference caused to the radar is low enough. For a given separation distance, the interference time for all active base stations is then summed up. If it exceeds the acceptable interference time for the radar (assumed to be 0.001%), the separation distance is increased a small step. This is repeated until the separation distance is large enough for the interference time to be sufficiently low, or the upper bound of the separation distance (here 150 km) is reached. The upper bound for the separation distance is given by the need to have a sufficient number of base stations active beyond that distance, in order not to underestimate the interference to the radar.

One may also want to consider a solution where one accepts placement of base stations in such a way that the total time of too high interference exceeds the 0.001% suggested above. It would then be necessary to occasionally switch off (or decrease the power of) the base stations, when excessive interference is detected due to anomalous propagation. IMT traffic would then have to utilize another set of frequencies.

It should be noted that separation distances were also calculated for a smooth earth for micro cellular base stations. The results were the same. This of course depends on the particular area chosen for the analysis.

5 Evaluation methodology

5.1 Radar to cellular interference

The results for radar to cellular interference are not derived from extensive system simulation results, but rather link level simulations coupled with the general characteristics of IMT-2000. However, the pulsed characteristics of the radars together with the error correcting features of IMT networks imply that this type of interference must be studied with some care. A few different methods have been used, and are presented in § 7.2.

5.2 Cellular to radar interference: Methodology for single and aggregate base stations

Throughout this study we assume that IMT base stations are constantly transmitting at their maximum power. This is a conservative assumption, but has the advantage of greatly simplifying the simulation analysis, and is also in line with the life-saving characteristics of radars as discussed above. The computer simulations are thus not dynamic in relation to the IMT networks, but are instead reduced to summing up the interference from all base stations of the IMT network at the radar receiver. It should be noted however that the simulations are dynamic in the sense that the radar rotation has been considered, to find the angle where the radar experiences the largest amount of interference.

The basis for the analysis is thus the following link budget describing the interference level at the radar from a single IMT base station:

$$Pr = Pt + Gt + Gr - Lp - FDR - PMr - Rt - Rr \qquad (5)$$

Pr: interfering power at receiver

Pt: transmitter output power

Gt: gain of transmitting antenna in the direction of the receiver

Gr: gain of receiving antenna in the direction of the transmitter

Lp: attenuation due to propagation effects

FDR: frequency dependent rejection

PMr: polarization mismatch at the receiver

Rt: insertion loss at transmitter

Rr: insertion loss at receiver.

Polarization loss is here set to zero. This is in line with the worst-case analysis that is assumed due to the life-saving characteristics of the radars in this band.

As we will see, it is in many cases necessary to have a certain guard band between the IMT emissions and the radar frequency, to decrease the level of interference to an acceptable level. This is described by the term FDR in equation (5), which depends on the frequency separation, the selectivity of the radar receiver and the ACLR of the IMT base station. When the assigned carrier frequencies for IMT and radar are not the same, the FDR is used as a correction factor to describe the additional protection due to the guard band.

In the case of aggregate interference to the radar, from several IMT base stations, one should here use the methodology for short-term interference described in § 4.

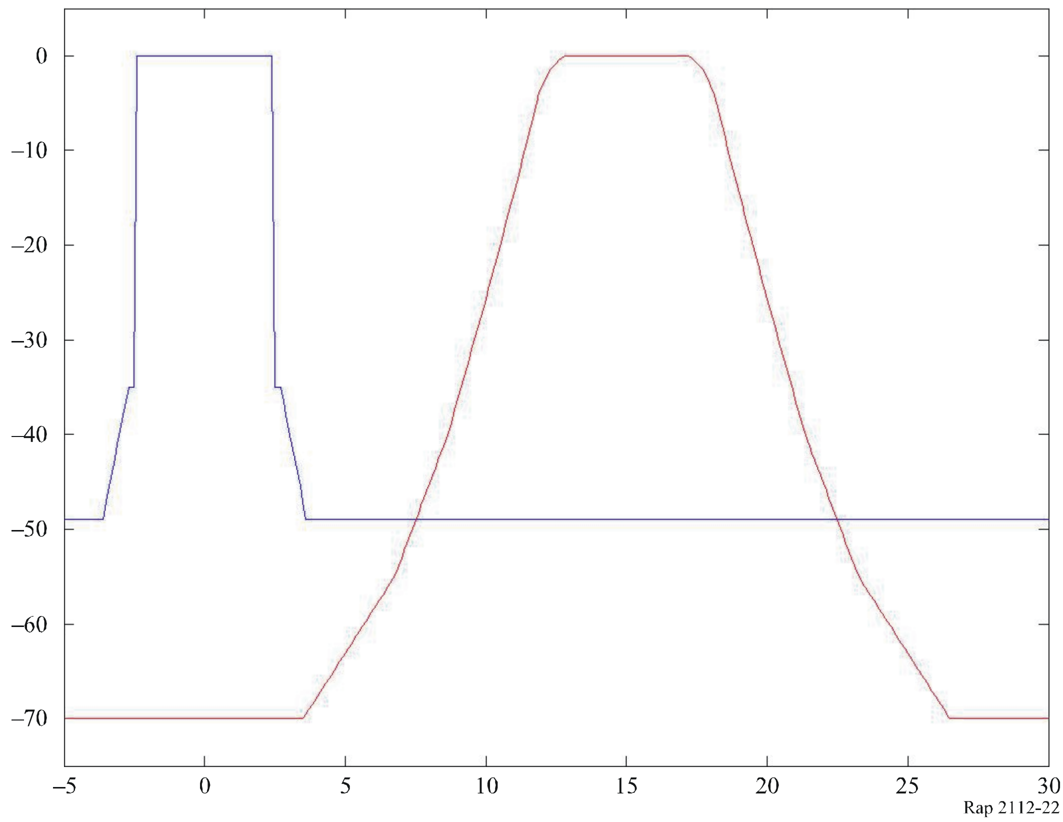
5.3 Frequency dependent rejection

Frequency dependent rejection (FDR) describes the additional interference protection provided when the carrier frequencies of the interfering transmitter and the interfered receiver are not the same. The size of this protection depends on the bandwidths of the transmitter and the receiver, frequency separation, the emission mask of the transmitter and the selectivity of the receiver. Figure 22 shows the emission mask of IMT-2000, and an example of radar selectivity. It must be noted that this figure does not represent the actual situation in the 2.7-2.9 GHz band. In reality, there may several radar or IMT carriers present, as well as so-called mirror images of the radar frequencies. The figure is merely designed to represent a possible relationship between one IMT and one radar carrier.

In this text it was decided to present the results as a function of FDR directly, i.e. not as a function of the three FDR input parameters. The main reason for this is that different radars have different selectivity characteristics, and would otherwise require separate calculations. Here a simple observation is used instead, that the same FDR can be obtained for different radars by using different frequency separation.

FIGURE 22

Emission mask for IMT (blue) and example of selectivity mask (red) for radar



The approach is simplified further by the fact that the main FDR cases studied correspond to either having the same carrier frequencies, or having frequency separation so large that only the minimum levels need to be taken into account. In the example in the figure, the FDR would be 0 dB (roughly) if the IMT base station and the radar used the same frequency. However, if they were separated as the figure indicates, the FDR would be close to 50 dB. In that case, it is also clear that the IMT base station emission mask is limiting the FDR protection.

It is important to note that for frequency separation to be possible, the band cannot be fully occupied by radars. Adjacent channel analysis relies on the availability of sufficient unused bandwidth for the IMT carrier and necessary guard bands.

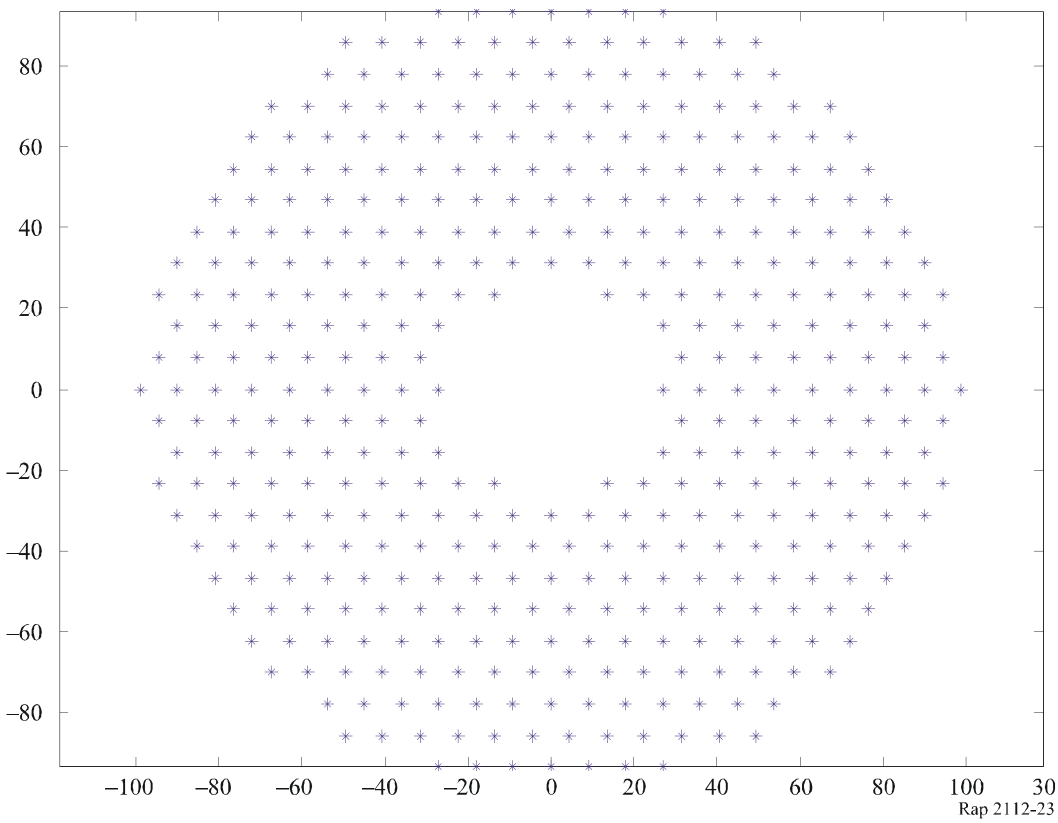
It should be noted that this approach also includes the usage of the mitigation technique base station front-end filter, since it can be incorporated in the emission mask of the transmitter.

6 Deployment scenarios studied

In a Hexagonal deployment of 3-sector macro cellular base stations, the cell radius is 3.5 km, in other words, the site-to-site distance is roughly 5 km. The base stations are evenly deployed in a hexagonal pattern starting at the specified separation distance and stretching 250 km (smaller distance used in figure) in all directions from the radar. It should be noted that since the deployment is centered around the origin (i.e. the position of the radar), it is not possible for the macro cellular base stations to be closer than about 5 km to the radar station in the simulations (see Fig. 23).

FIGURE 23

The hexagonal deployment scenario for macro cellular base stations

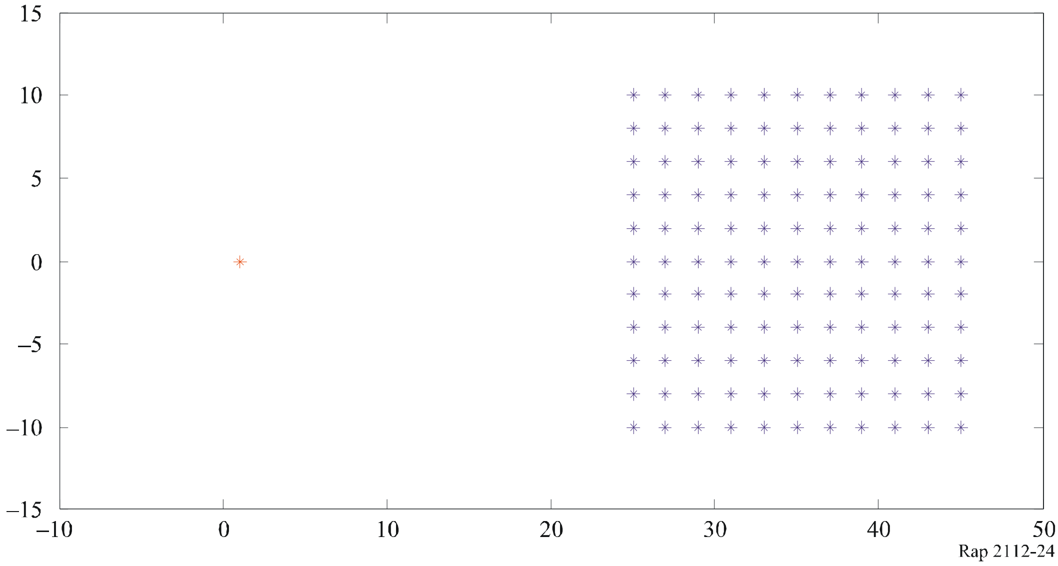


Note that distances in the figure are not the same as those used in the simulations.

City deployment of micro and pico cellular base stations. The base stations are placed in a square city with a side of 10 km for micro base stations and 2 km for pico base stations, on a grid with site-to-site distance 0.5 km for micro cells and 0.2 km for pico cells. The radar is located a specified separation distance away from the closest base station, and the radar antenna points directly towards the city (see Fig. 24).

FIGURE 24

The city deployment scenario for micro and pico cellular base stations



Note that distances in the figure are not the same as those used in the simulations.

7 Results

7.1 Radar as victim system, no mitigation techniques

7.1.1 Interference from IMT macro base stations

This section contains results for interference from macro base stations to radars without mitigation techniques applied. Table 17 contains a summary of the results for IMT-2000, and Table 18 contains the IMT-Advanced results.

TABLE 17

Separation distance (km) requirements for successful co-existence between Radar A and Radar G and macro cellular IMT-2000, no mitigation techniques applied

BS type	Scenario	FDR (dB)	Radar A required separation (km)	Radar G required separation (km)
Macro	Hex	0	>150	>150
		50	>150	>150

TABLE 18

Separation distance (km) requirements for successful co-existence between Radar A and Radar G and macro cellular IMT-Advanced, no mitigation techniques applied

BS type	Scenario	FDR (dB)	Radar A required separation (km)	Radar G required separation (km)
Macro	Hex	0	>150	>150
		50	>150	>150

7.1.2 Interference from IMT micro base stations

The micro base stations differ from the macro base stations in antenna height, output power, antenna pattern, and propagation characteristics, due to the lower placement of the antennas. This gives a considerably lower interference than for the macro base station case. Tables 19 and 20 contain summaries of required separation distances for IMT-2000 and IMT-Advanced, respectively. Note that the IMT-2000 micro base stations are assumed to have 8 dB higher output power than the IMT-Advanced micro base stations.

TABLE 19

Separation requirements for successful co-existence between Radar A and Radar G and micro cellular IMT-2000, no mitigation techniques applied

BS type	Scenario	FDR (dB)	Radar A required separation (km)	Radar G required separation (km)
Micro	City	0	>150	>150
		50	>150	>150

TABLE 20

Separation requirements for successful co-existence between Radar A and Radar G and micro cellular IMT-Advanced, no mitigation techniques applied

BS type	Scenario	FDR (dB)	Radar A required separation (km)	Radar G required separation (km)
Micro	City	0	>150	>150
		50	128	>150

7.1.3 Interference from IMT pico base stations

Table 21 contains the results for the pico base station interference scenarios without mitigation. Pico base stations will produce even lower interference than micro base stations, mainly due to lower output power, but also due to lower placement of the antenna.

TABLE 21

Separation requirements for successful co-existence between Radar A and Radar G and pico cellular IMT-2000, no mitigation techniques applied

BS type	Scenario	FDR (dB)	Radar A required separation (km)	Radar G required separation (km)
Pico	City	0	>150	>150
		50	19	>150

TABLE 22

Separation requirements for successful co-existence between Radar A and Radar G and pico cellular IMT-Advanced, no mitigation techniques applied

BS type	Scenario	FDR (dB)	Radar A required separation (km)	Radar G required separation (km)
Pico	City	0	>150	>150
		50	18	>150

7.1.4 Interference from IMT to other types of radars

The results above have been obtained for Radar A and G. To obtain results for other kinds of radar, we have to take into account different interference sensitivity levels, receiver bandwidths, antenna azimuthal beamwidths and antenna gain of the main beam. For instance, Radar type B has considerably lower tolerance for interference, –121.9 dBm, similar antenna gain and azimuthal beam width, but also a considerably lower bandwidth. All in all, this radar type will thus be able to handle similar scenarios of interfering IMT-2000 base stations. This is also true for the other radars listed in Table 16.

7.2 IMT as victim system

The effects of radar interference on IMT terminals have been divided into two areas. The first concerns the effects on certain important parts of the receiver chain, LNA, AGC and ADC. These are treated in § 7.2.1 and in Appendix 3 to this Annex, where it is shown that a properly designed terminal will not suffer greatly from radar interference.

The second area is that of quality of service degradation, i.e. higher bit error rate (BER), frame error rate (FER), etc due to erasure of symbols when there is radar interference. This is discussed in § 7.2.2 and Appendix 3 to this Annex, where the results show that there will only be small effects on the overall quality of the IMT services.

7.2.1 Effects on LNA, AGC and ADC

A concern that must be studied is the phenomenon of transient effects in the receiver chain, after a radar pulse, before normal operation is achieved again. In other words, there might be a “recovery time” for e.g. the AGC after each radar pulse, extending the period during which an IMT receiver is negatively affected.

The key to solving such problems is appropriate receiver design. For instance, signal power to be used by the AGC can be measured after the A/D-converter, resulting in hard limiting of the high amplitude pulses. Also, the signal power can be averaged over a longer time period, several micro seconds, further reducing the effects on the AGC. Appendix 3 to this Annex describes in detail how this can be accomplished for LNA, AGC and ADC.

7.2.2 Quality of service degradation due to pulsed radar interference

A sufficiently high carrier to interference to noise ratio is necessary for satisfactory operation of IMT. However, it is necessary to take into account that IMT-2000 and similar systems employ techniques such as forward error correction (FEC) and time interleaving to combat the interference that is always present in spectrum efficient cellular systems. For packet data services one may of course also resort to the alternative of retransmissions. This means that temporary interference may be acceptable if not too frequent or and extended in time, and it is thus not sufficient to consider the power of radar interference when such interference is present. Rather a temporal aspect must be taken into account, also including the error correction mechanisms present in current and future IMT networks.

In this section a rather straightforward analysis is presented, intended to give a basic understanding for how radar interference affects IMT performance. Appendix 3 to this Annex contains an alternative, more detailed analysis.

It is convenient to divide radars into different groups when analysing the effects of radar interference. Three typical cases have been considered here, short and long pulse radar, as well as one intermediate case:

Pulse width: 1.0 micro s Pulse repetition rate: 1 000/s

Pulse width: 5.0 micro s Pulse repetition rate: 500/s

Pulse width: 90 micro s Pulse repetition rate: 1 000/s

It is also convenient to consider different types of IMT systems based on CDMA or OFDM technology. Although IMT-Advanced systems have not been specified yet, it is not unreasonable to assume that one of the above technologies will be used.

Please note that in the simplified analysis below, it is assumed that the radar analysis is always so strong that the affected symbols are always erased. This is of course a pessimistic assumption.

OFDM analysis

The considered OFDM system has the following basic parameters:

50 μs symbol time (including cyclic prefix), that is roughly 20 kHz subcarrier spacing.

Interleaving of code blocks over frames of size 10 OFDM symbols (and a number of subcarriers, the exact number of which will not matter to the following discussion).

The values are two large extent motivated by external design constraints such as typical delay spreads, Doppler effects, frequency synchronization accuracy, etc, and hence parameters of the same order of magnitude will typically be found in any cellular radio communication systems based on OFDM.

First consider a radar pulse length of 1 μs, with a pulse repetition rate of about 1 000 pulses per second. Even if a reasonable time dispersion is included, each pulse will then in most cases only affect one OFDM symbol. Assuming the worst case, where the entire affected OFDM symbol has to be discarded, we find that 1/10 of a frame is erased. This will happen approximately every second frame. In total, 5% of all OFDM symbols can thus be considered erased.

To understand the effects of this on transmission with different delay requirements, consider first data transmission without extreme delay requirements. In a well-designed system, with adequate interleaving and state-of-the-art coding, the throughput is according to information theory (Elements of Information Theory, Thomas M. Cover, Joy A. Thomas) essentially the conveyed mutual information between sender and transmitter. An erasure of 5% would mean a 5% reduction of the conveyed mutual information, and thus according to this reasoning a throughput reduction of about 5%.

We then consider transmission of real-time type, with tighter delay requirements for which retransmissions are generally speaking less acceptable. Assuming that the system is unable to predict which frames will be affected by pulses, the system may have to adapt to the worst-case of 10% erasure, for example by decreasing the code rate by 10% in every frame. The throughput reduction would thus be about 10%.

Now consider a pulse length of 5 μs, with a repetition rate of 500 pulses per second. Again, we find that each pulse will typically affect only one OFDM symbol. However, in this case, only about every fourth frame will be affected. For transmission without extreme delay requirements, this will give a throughput reduction of about 2.5%. For transmission of real-time type, we may have still to accept a throughput reduction of about 10%.

Finally, consider a pulse length of about 90 μs, with a repetition rate of about 1 000 pulses per second. Each pulse will then typically affect two or three OFDM symbols. A conservative approach is to assume that three OFDM symbols being erased. This will happen every second frame on average. Without extreme delay requirements, this will give a throughput reduction of about 15%. For transmission of real-time type, the reduction may be about 30%, again assuming that the system has no possibility of predicting where pulses will occur.

CDMA analysis

Assume that the system in question has the following characteristics:

2.6 * 10^(–7) s chip length

Spreading factor (SF) 16

Block length 2 ms

480 symbols per TTI and code.

For the first radar type, with pulse length of 1 μs and repetition rate 1 000 pulses/s, the number of "destroyed" chips per radar pulse will be 4, which results in ceil(4/16) = 1 destroyed symbol per radar pulse. Since there will be 2 radar pulses per TTI, we get 2 destroyed symbols per code and TTI, corresponding to 2/480 = 0.4% erroneous symbols and 0.4% erroneous bits.

For the second case, 5 μs pulse length and repetition rate 500 pulses/s, a similar analysis will result in 1.7 % erroneous bits. Finally, for the worst case 90 μs pulse length and 1 000 pulses/second, the bit error rate will be 9.6%. Note again that in all cases it is assumed that the radar interference is so strong that there will be complete erasure in all cases.

To understand the effects of this bit rate on system performance, consider Fig. 8-12, p 356, in Ref. (Error-Correction Coding for Digital Communications, George C. Clark and J. Bibb Cain). For a reasonable working point error rate, Pb in the range 10^(-3) to 10^(-4), and a random erasure rate according to the above between 0.4 and 9.6%, this corresponds to a loss of no more than 1dB in E_b/N_0. On top of that, it should be noted that very rudimentary coding is considered in this example, and more efficient coding schemes are used in modern communication systems.

One may also note that a similar analysis has been carried out by Ofcom, Ref. (Technical Study, Adjacent and In-Band Compatibility Assessment for 2 500-2 690 MHz, 11 December 2006, Ofcom). The conclusions are the same, "TWT and magnetron radars are not expected to cause significant degradation to UMTS or WiMAX services if they are deployed in the award band". Furthermore, in Ref. (Error-Correction Coding for Digital Communications, George C. Clark and J. Bibb Cain), one can find the following information, describing the effects of bursty noise resulting in erased symbols: "The spacing between bursts can assume several forms. One such process is the periodic burst erasure process. In this case a burst of *B* symbol erasures occurs every *P* symbols. A typical example of such an interference process is RFI from an interfering pulse radar. We will find that in many cases this type of burst erasure process does not significantly degrade the performance of random-error-correcting codes even when no interleaving is used". It should be noticed that also interleaving is used in modern cellular systems such as IMT networks, providing further protection from interference.

Finally it should be noted that the QoS degradation may become more serious in case there are several radars interfering an IMT device simultaneously.

7.3 Radar as victim system, mitigation techniques used

The mitigation techniques used in this section are the following:

Clutter protection. This refers to propagation model modifications for micro and pico base stations located in an environment with buildings or other obstacles. The modifications to propagation model P.452 for this case have been provided by ITU-R WP 3M, and can be found in Appendix 1 to this Annex. This is not used for macro base stations due to their placement well above roof-level of surrounding buildings. This technique is in fact frequently used in network deployment in cities, where intra-system interference is controlled by the shielding effects of the surrounding building.

BS front-end filters. It is possible to provide additional protection on top of the ACLR of the IMT systems outside their assigned carrier. A filter providing an additional 40 dB suppression of the adjacent channel interference for all signals more than 5 MHz outside the 5 or 10 MHz assigned IMT channel has been used in the simulations. (Note that such filters are already in use in cellular networks. Annex 2 contains an example of such a filter. The size of the guard band, here suggested to be 5 MHz as a conservative value, can be decreased by using more advanced filters, e.g. ceramic filters.) It should be noted that although such front-end filters would cause an additional cost to the IMT network operators, this cost does not affect the radar systems. See also Recommendation ITU-R M.2045, Annex 5. This front-end filter results in a maximum suppression of the IMT interference since it has an impact on the FDR between IMT and radar roughly –90 dB. Assuming the radar mask of Fig. 22 this front-end filter would result in an improved FDR up to 65 dB as far as the frequency separation between IMT and radar is roughly higher than 10 MHz. This FDR could possibly be increased up to 90 dB but would then require a considerably larger frequency separation.

Sector blanking. This only applies to sectorized IMT macro cells. It is an important observation that certain sectors of the IMT network will interfere with a particular radar considerably more than others, in specific those whose antennas are directed towards the radar. One may thus for those sectors want to avoid the frequency and adjacent frequencies of the radar station, whereas the other sectors of the network may very well use those. This of course relies on having other frequencies available for the sectors where blanking is applied. This is akin to the frequency planning of cellular networks, i.e. an identification that a certain receiver is incompatible with a number of different transmitters, but not all. The assumption here is that no sector in the IMT network will have an antenna gain in the direction of the radar which is higher than –10 dBi, which is achieved either by blanking as suggested above, or the usage of adaptive antennas in the case where a smaller decrease in interference is required. This corresponds to having the radar station offset at least 90° from the IMT antenna bore sight. This mitigation technique could provide an approximate 30 dB interference suppression. Sector blanking may be less efficient in a scenario with multiple radars present, located in different directions from the set of base stations in question. This may require blanking in such a large number of sectors that it could limit the use of corresponding channels for the IMT network.

Temporary muting. This is based on the fact that the IMT network may carry services that are not dependent on real-time delivery, and the rotation of the radar. Thus it may be possible to decrease the interference received by the radar by switching off/decreasing power of the IMT base stations in the direction of the radar antenna. In the simulations it is assumed that a “slice” of 15° (± 7.5° around bore sight of antenna) is quiet. This requires knowledge of the radar antenna main beam direction, either based on measurements combined with the regularity of the rotation (if that is the case) or advance information distributed by the radar station. This mitigation technique could provide an approximate maximum 50 dB interference suppression corresponding to the radar antenna discrimination between main and side lobes. Explanations to be provided by United States of America and France on the limitations of such an approach. There is currently no functionality present in radar systems that supports such a feature. It should also be noted that some radar operators may not be willing to disclose the information necessary for this mitigation technique.

Tables 23 and 24 contain results for IMT-2000 and IMT-Advanced, respectively, for the macro cellular cases Tables 25 and 26 contain the results for micro base stations and 14 and 15 those for pico cellular deployment. The results here apply to Radar A and G. For conclusions regarding other types of radar, see § 7.1.4. Again, it should be noted that separation distances were also calculated for a smooth earth, for micro cellular base stations. The results were the same. This of course depends on the particular area chosen for the analysis.

TABLE 23

Separation requirements for successful co-existence between Radar A and Radar G and macro cellular IMT-2000, with mitigation techniques applied

BS type	Scenario	FDR (dB)	Muting	Blanking	Radar A required separation (km)	Radar G required separation (km)
Macro	Hex	90			15	>150
		0	X		>150	>150
		50	X		34	>150
		65	X		<5	48
		90	X		<5	<5
		0		X	>150	>150
		50		X	68	>150
		65		X	10	147
		90		X	<5	<5
		0	X	X	>150	>150
		50	X	X	<5	18
		65	X	X	<5	<5
		90	X	X	<5	<5

TABLE 24

Separation requirements for successful co-existence between Radar A and Radar G and macro cellular IMT-Advanced, with mitigation techniques applied

BS type	Scenario	FDR (dB)	Muting	Blanking	Radar A required separation (km)	Radar G required separation (km)
Macro	Hex	90			10	147
		0	X		>150	>150
		50	X		34	>150
		65	X		<5	47
		90	X		<5	<5
		0		X	>150	>150
		50		X	57	>150
		65		X	10	131
		90		X	<5	<5
		0	X	X	>150	>150
		50	X	X	<5	<5
		65	X	X	<5	<5
		90	X	X	<5	<5

TABLE 25

Separation requirements for successful co-existence between Radar A and Radar G and micro cellular IMT-2000, with mitigation techniques applied

BS type	Scenario	FDR (dB)	Muting	Clutter	Radar A required separation (km)	Radar G required separation (km)
Micro	City	90			<1	34
		0	X		>150	>150
		50	X		<1	35
		65	X		<1	2
		90	X		<1	<1
		0		X	>150	>150
		50		X	>150	>150
		65		X	27	>150
		90		X	<1	30
		0	X	X	>150	>150
		50	X	X	<1	14
		65	X	X	<1	<1
		90	X	X	<1	<1

TABLE 26

Separation requirements for successful co-existence between Radar A and Radar G and micro cellular IMT-Advanced, with mitigation techniques applied

BS type	Scenario	FDR (dB)	Muting	Clutter	Radar A required separation (km)	Radar G required separation (km)
Micro	City	90			<1	10
		0	X		>150	>150
		50	X		<1	24
		65	X		<1	<1
		90	X		<1	<1
		0		X	>150	>150
		50		X	29	>150
		65		X	3	132
		90		X	<1	3
		0	X	X	>150	>150
		50	X	X	<1	3
		65	X	X	<1	<1
		90	X	X	<1	<1

TABLE 27

Separation requirements for successful co-existence between Radar A and Radar G and pico cellular IMT-2000, with mitigation techniques applied

BS type	Scenario	FDR (dB)	Muting	Clutter	Radar A required separation (km)	Radar G required separation (km)
Pico	City	90			<1	<1
		0	X		>150	>150
		50	X		<1	<1
		65	X		<1	<1
		90	X		<1	<1
		0		X	>150	>150
		50		X	7	>150
		65		X	<1	38
		90		X	<1	<1
		0	X	X	96	>150
		50	X	X	<1	<1
		65	X	X	<1	<1
		90	X	X	<1	<1

TABLE 28

Separation requirements for successful co-existence between Radar A and Radar G and pico cellular IMT-Advanced, with mitigation techniques applied

BS type	Scenario	FDR (dB)	Muting	Clutter	Radar A required separation (km)	Radar G required separation (km)
Pico	City	90			<1	<1
		0	X		>150	>150
		50	X		<1	<1
		65	X		<1	<1
		90	X		<1	<1
		0		X	>150	>150
		50		X	5	145
		65		X	<1	37
		90		X	<1	<1
		0	X	X	73	>150
		50	X	X	<1	<1
		65	X	X	<1	<1
		90	X	X	<1	<1

8 Conclusion

Please refer to the conclusions in § 4 of the this Report.

Appendix 1
to Annex 2

Clutter loss modifications to propagation model ITU-R P.452

Recommendation ITU-R P.452 is formulated primarily for uncluttered antennas. It includes a somewhat simplistic site-shielding model, originally intended to estimate additional losses due to urban shielding of a small-aperture earth station.

The following additional method, to be used in conjunction with Recommendation ITU-R P.452, can be suggested from the development of a path-specific prediction model based on Recommendation ITU-R P.452 currently under preparation in WP 3K. This method is applicable over the frequency range 700 MHz to 6 GHz.

A terrain profile must be available for each path for which a prediction is required. It is preferable that the profile points are equally spaced along the path. The height of each profile point except for the first and last, that is, the locations of the terminals, should be raised by 10 m. If either terminal is less than 10 m above the ground its height should be taken as 10 m for the Recommendation ITU-R P.452 calculation. If a terminal is more than 10 m above the ground, its height should be left unchanged for the Recommendation ITU-R P.452 calculation.

For either terminal, if it is actually less than 10 m above the ground, a correction is then added to the basic transmission loss calculated by Recommendation ITU-R P.452 as described above. The correction is given by:

$$\text{Correction} = \mathrm{J}(\nu) - 6.03 \qquad \text{dB} \tag{6}$$

where:

$$J(\nu) = \left[6.9 + 20\log\left(\sqrt{(\nu - 0.1)^2 + 1} + \nu - 0.1\right)\right] \tag{6a}$$

$$v = Knu\sqrt{h_{dif}\theta_{clut}} \tag{6b}$$

$$hdif = R - h \qquad \text{m} \tag{6c}$$

$$\theta clut = \arctan(hdif / 27) \qquad \text{degrees} \tag{6d}$$

$$Knu = 0.0108\sqrt{f} \tag{6e}$$

h: antenna height above ground (m)

R: 10 m

f: frequency (MHz).

Thus the above correction is not used if both terminals are 10 m or more above the ground, used once if one terminal is less than 10 m above ground, and used twice if both are less than 10 m above ground.

The basic transmission loss calculated from Recommendation ITU-R P.452, with the terminal-height corrections if applicable, take into account the effect of clutter and the proximity of the ground for a typical path.

The statistics of location variability can be accounted for in a simple manner as follows. For either terminal, if less than 10 m above ground, assume a standard deviation given by:

$$\sigma = 5 \cdot (1 - 0.1\,h) \qquad \text{dB}$$

If both terminal are less than 10 m above ground, combine the standard deviations according to $\sigma = \sqrt{\sigma_t^2 + \sigma_r^2}$. Assume a normal distribution in dB and calculate the correction for the required probability. Limit this correction such that the sum of the terminal-height and location-variability corrections is not negative, that is, taken together they do not increase signal level above the Recommendation ITU-R P.452 result.

Appendix 2
to Annex 2

IMT base station front-end filters

This Annex contains information on the design of base station filters that would be applicable to IMT-2000 as well as IMT-Advanced. For all cases an attenuation of 60 dB is obtained. The complexity of the filters will depend on how low insertion loss is required. The filters have been derived for frequencies around 2.6 GHz, but would be equally applicable in the 2.7-2.9 GHz band.

10 MHz guard band and 10 MHz passband

Q = 5000 => filter with ordinary metal rods.

Q = 6000 => filter with ordinary metal rods.

Q = 8000 => ceramic filter

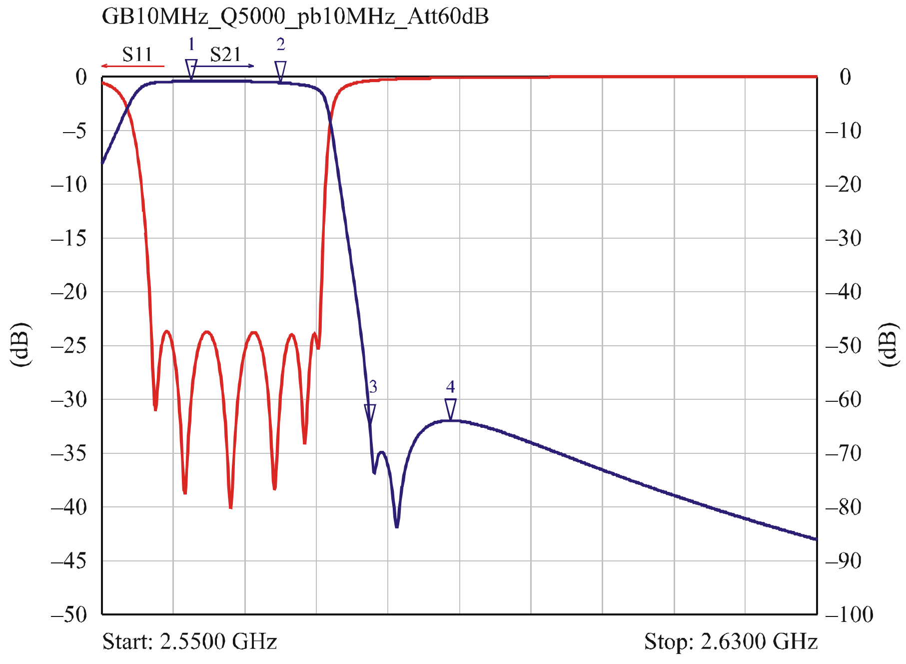
Q = 12000 => ceramic filter

Q = 20000 => ceramic filter. There is a risk that this *Q*-value can not be achieved.

Attenuation 60 dB

	***Q* = 5000**	***Q* = 8000**	***Q* = 12000**
Insertion loss at 2 570 MHz (6p+2tz)	–1.1 dB	–0.7 dB	–0.5 dB

NOTE 1 – Insertion loss at room temperature.



Mkr	Trace	X-Axis	Value	Notes
1 ▽	S21	2.5600 GHz	–0.84 dB	
2 ▽	S21	2.5700 GHz	–1.11 dB	
3 ▽	S21	2.5800 GHz	–64.99 dB	
4 ▽	S21	2.5890 GHz	–63.94 dB	

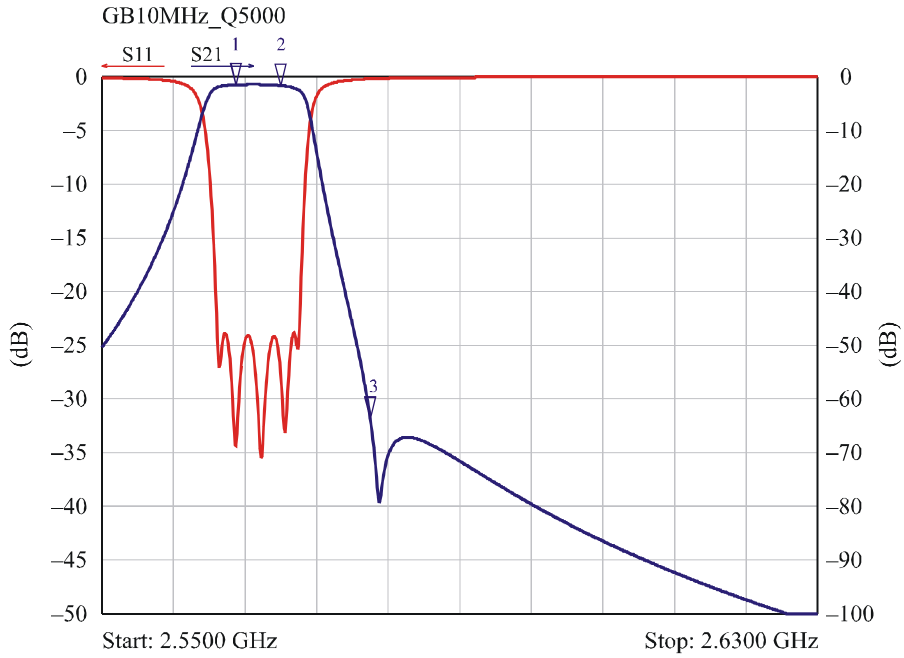
Rap 2112-App2an2-01

10 MHz guard band and 5 MHz passband

60 dB attenuation

	***Q* = 5000**	***Q* = 6000**	***Q* = 8000**	***Q* = 12000**
Insertion loss at 2 570 MHz (5p+tz)	–1.6 dB	–1.4 dB	–1.0 dB	–0.8 dB
Insertion loss at 2 570 MHz (6p+2tz, same as for 10 MHz gb and 10 MHz pb)	–1.1 dB	–0.9 dB	–0.7 dB	–0.5 dB

NOTE 1 – Insertion loss at room temperature.



Mkr	Trace	X-Axis	Value	Notes
1 ∇	S21	2.5650 GHz	–1.46 dB	
2 ∇	S21	2.5700 GHz	–1.64 dB	
3 ∇	S21	2.5800 GHz	–63.59 dB	

Rap 2112-App2an2-02

Above: Filter with five poles and one transmission zero.

Appendix 3
to Annex 2

Detailed analysis of radar interference to IMT terminals

I Short radar pulses

1 Introduction

This contribution is a theoretical investigation of the interference mechanism from short radar pulses to a IMT-2000/WCDMA mobile receiver in the 2.7-2.9 GHz band. It leads to the conclusion that the interference effects to IMT-2000/WCDMA are negligible, even in the co-channel case.

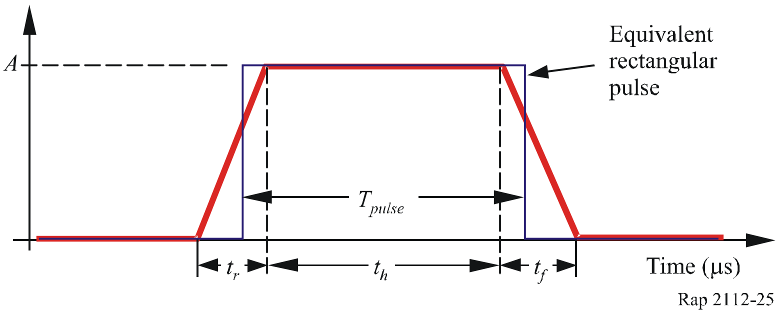
2 Characteristic of the radar interference

According to an ITU-R Recommendation for interference analysis the radar signal shall be assumed as a sequence of pulses with trapezoidal shape with hold time t_h, rise time t_r and fall time t_f (Fig. 25). The total energy of this pulse is given by $A2(t_h+(t_r+t_f)/3)$. In order to simplify the following considerations this pulse is replaced by an equivalent rectangular pulse with same amplitude and same pulse energy. A rectangular pulse with amplitude A and width T_{pulse} has the energy A2Tpulse. The assumption of same energy results in a pulse duration of:

$$T_{pulse} = t_h + \frac{t_f + t_r}{3}$$

FIGURE 25

Trapezoidal radar pulse and its rectangular equivalent



For numerical analysis and simulations we assume the following parameters:

t_r = 0,2 µs (rise time)

t_f = 0,2 µs (fall time)

t_h = 0,8 µs (hold time).

The width of an equivalent rectangular pulse is then T_{pulse} = 0,933 µs ≈ 1 µs.

Another characteristic of the radar pulse sequence is the pulse repetition period, here denoted as TPRP. This period is typically in the order of 1 ms.

3 Mechanism of radar interference to IMT-2000/WCDMA downlink receiver

3.1 General

IMT-2000/WCDMA is based on spread spectrum techniques. The spreading factors are powers of 2 and can range from 4 to 512. With a chip rate of 3.84 Mchip/s this result in symbol lengths ranging from 1.04 to 133 µs.

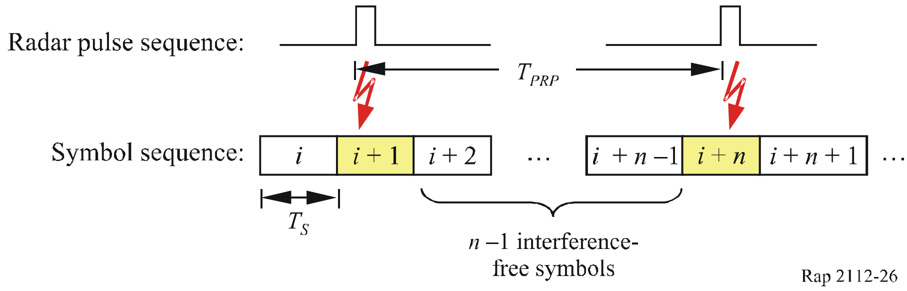
Compared to the IMT-2000/WCDMA symbol lengths, the radar interference can be assumed to have the following properties:

The pulse duration is less than the symbol duration in IMT-2000/WCDMA. For large spreading factors most pulses hit only one symbol, some may hit two consecutive symbols.

The pulse repetition period is much greater than the largest symbol duration. This implies that only a fraction of all symbols is affected by radar interference (Fig. 26).

FIGURE 26

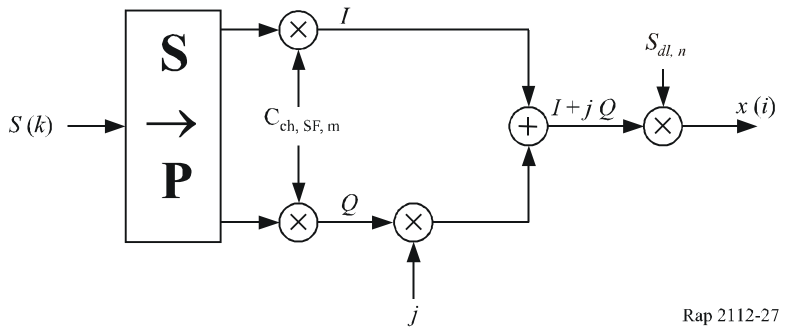
Interference from radar pulses to an IMT-2000/WCDMA data sequence



In IMT-2000/WCDMA the binary data symbols are mapped to QAM symbols, then multiplied by a binary channelisation spreading code with values 1 or -1 and multiplied by a complex scrambling sequence whose elements can be either $1+j$, $–1+j$, $–1–j$ or $1–j$ (Fig. 27). For the assessment of the effect from external interference which is statistically independent from the useful signal, only the scrambling sequence is relevant.

FIGURE 27

Signal spreading for the physical channels in IMT-2000/WCDMA downlink



The receiver is based on a RAKE-structure. Each RAKE-finger consists of a despreader, in which the received signal is multiplied with the complex conjugate of the scrambling sequence $S_{dl,n}$ and with the channelisation sequence C_{ch}, both time-aligned with the received signal. The accumulation of SF chips result in the estimated (analogue) symbol for this RAKE-finger. (SF = spreading factor = number of chips per symbol). The weighted average of the phase-aligned outputs of the RAKE-fingers is finally the decision variable for the estimation of the symbol sequence $S(k)$.

3.2 Effect of radar pulses on a linear spread spectrum receiver

The quantity of interest is the signal-to-noise ratio of this decision variable. For a first assessment it is sufficient to consider one RAKE-finger only. It is well-known for spread spectrum systems that the amplitude of the desired signal after the despreader is proportional to the spreading factor SF and hence its power is proportional to SF2. It is also well-known that the power of a random interfering signal is proportional to SF if the signal energy is equally distributed over the symbol interval. This gives the well-known spreading gain of SF in the signal-to-noise ratio after despreading.

The following considerations are valid for radar pulses which are shorter than the shortest IMT-2000/WCDMA symbol length. Compared to a noise-like interferer with a power that is the same as the peak-power of the radar pulse, the power after despreading is reduced by the ratio of the pulse duration T_{Pulse} to the symbol length T_S. Therefore the signal-to-noise ratio after despreading is given by:

$$SRR = SRR_0 + 10 \log\left(SF \frac{T_S}{T_{Pulse}} \right) \qquad \text{(dB)}$$

SRR0 is the ratio of the signal power to the peak pulse power at the input of the despreader. In order to indicate that the only interference source in this relation is the radar pulse, we introduced the notation SRR for signal to radar interference ratio measured in dB.

Normalising all time intervals to the IMT-2000/WCDMA chip duration T_{chip}, and replacing the ratio T_S/T_{chip} by the spreading factor SF, this can be expressed as:

$$SRR = SRR_0 + 20 \log SF - 10 \log \frac{T_{pulse}}{T_{chip}}$$

This is a fundamental relation for any pulsed interference. It shows that the signal to peak power ratio is enhanced by the square of the spreading factor.

What is the effect on the bit error ratio? In IMT-2000/WCDMA the data symbols are quadrature amplitude modulated (QAM). Gray-mapping is applied. In the receiver these symbols are coherently demodulated. Assuming that the noise in the decision variable has approximately a Gaussian distribution, the bit error ratio can be assessed from the SRR using the well-known relation for QAM (or QPSK) with coherent demodulation which is given by:

$$BER_1 = Q\left(\sqrt{\gamma}\right) = \frac{1}{\sqrt{2\pi}} \int_{\sqrt{\gamma}}^{\infty} e^{-\frac{x^2}{2}} \, dx$$

with $\gamma = S/N = 10^{SNR/10}$ as the signal to noise ratio of the decision variable. (Note that for QAM $S/N = 2\ E_b/N_0$. The factor 2 reflects the fact that each symbol carries two bits.) If radar is the only active interference, SNR can be replaced by SRR.

The above consideration only holds for those symbols which are interfered by a radar pulse. BER1 can therefore be interpreted as a conditional bit error ratio under the condition that the information carrying symbols are interfered by a radar pulse. In order to get the over-all bit error ratio we need to take the other symbols also into account. Assuming radar interference only, i.e. all other interference is negligible, this can be obtained by multiplying the conditional bit error ratio by the ratio of the symbol length TS to the pulse repetition period TPRP. Normalising all time intervals to Tchip, the over-all bit error ratio can be expressed as:

$$BER(SRR_0) = \frac{SF}{T_{PRP} / T_{chip}} \cdot Q\left(10^{SRR_0/20} \cdot \frac{SF^2}{T_{pulse} / T_{chip}} \right)$$

Figure 28 shows this relation for all IMT-2000/WCDMA spreading factors and a pulse repetition period of T_{PRP} = 1ms. Doubling the spreading factor shifts the error curve by 6 dB to the right and multiplies it with a factor of 2 which corresponds to a vertical shift in a log-BER scale. In the limit ($SRR_0 \rightarrow -\infty$) the BER approaches its maximum which is given by the above equation when the Q-function approaches ½:

$$BER_{max} = \frac{SF}{T_{PRP} / T_{chip}} 0.5$$

TABLE 29

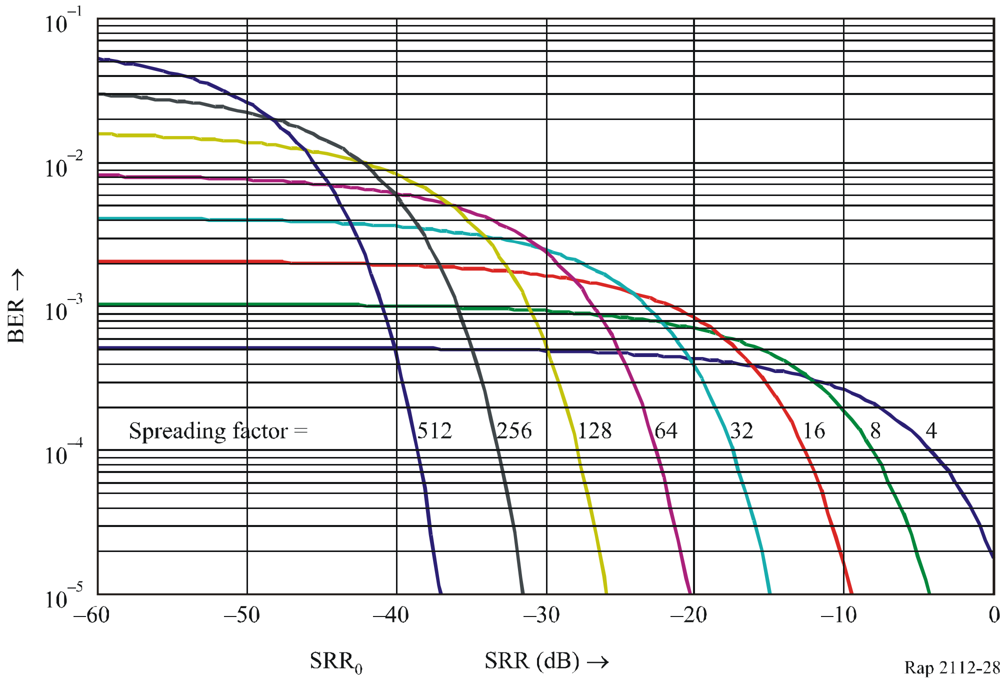
Maximal bit error rates in dep. on the spreading factor SF

SF	4	8	16	32	64	128	256	512
BER*max*	0.05%	0.10%	0.21%	0.42%	0.83%	1.67%	3.33%	6.67%

For high spreading factors the peak power of the radar pulse can be significantly higher than the power of the desired signal before it becomes noticeable.

FIGURE 28

Effect of radar co-channel interference to a linear IMT-2000/WCDMA receiver: raw-BER versus SRR_0 (signal-to-radar peak power ratio at RAKE-input)



3.3 Mitigation effects: Hard limiter and FEC

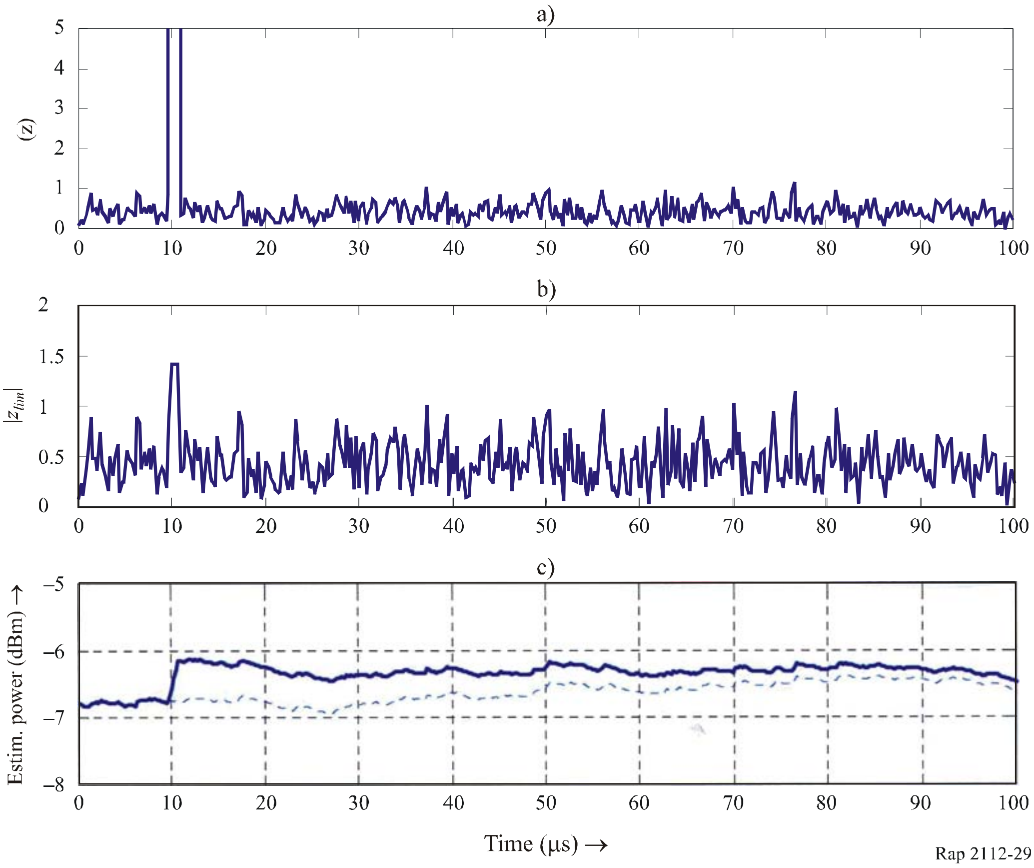
At this point it is important to take effects from a realistic implementation of a IMT-2000/WCDMA-receiver into account. Any implementation comprises two A/D-converters, (*I*- and *Q*-component) before the signal is fed into the RAKE-receiver. This device has inherently a hard limiter function. Any high amplitude impulse will be limited. The effect of this limitation depends on the load factor. (The load factor is the ratio of the standard deviation σ of the input signal to the maximal amplitude Amax of the A/D-converter.) Under normal operating conditions the optimal load factor is between –15 and –6 dB, depending on the quantizer resolution [Proakis, 1995a]. An AGC loop assures that the A/D-converter is operated around the optimal load factor. Figure 29a) and 29b) give an impression of the limiting effect. Figure 29c) is explained in the next section.

As a consequence, the SRR_0 has a lower limit which is exactly given by the actual load factor.

For spreading factors 16 and higher the BER for these values is really negligible.

For spreading factors 4 and 8 even the maximal BER is so low that the subsequent channel decoder can completely correct all these errors on top of errors from other interference. The forward error correction schemes in IMT-2000/WCDMA are designed such that the raw-BER can be in the order of 1-10% before residual errors occur. Therefore, additional error rates of 0.1% and less introduced by radar interference has no noticeable effect at all.

FIGURE 29



Sample signal with pulsed interferer:

a) input of A/D-converter

b) output of A/D-converter (load factor = –12 dB, A_{max} = 1)

c) estimated power for the AGC (|*zk*|2 filtered with 1st order recursive filter with τ = 60 µs).

It can be concluded that radar pulse interference has no significant effect on radio link quality in a IMT-2000/WCDMA receiver, thanks to the limiting effect from the A/D-converter and the strong forward error correction scheme.

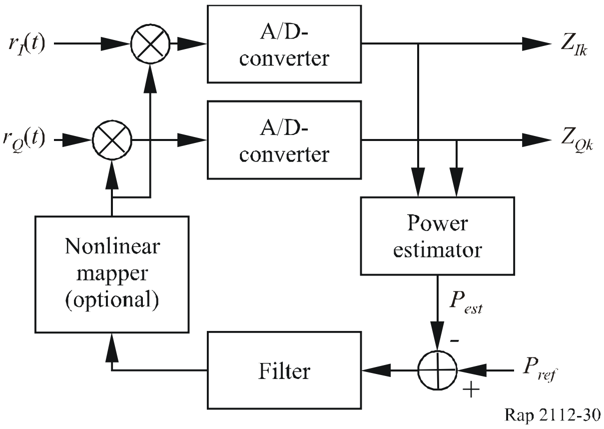
3.4 Automatic gain control (AGC)

There is still a critical issue which need to be addressed: As mentioned before, any IMT-2000/WCDMA receiver needs an AGC to control the load of the A/D-converter. This is especially important for the downlink in order to compensate fast fading effects. This amplifier gain set by the AGC is based on measurements of the average power of the input signal. Radar pulses with high peak powers might affect these measurements significantly, such that a low gain might be set with the consequence that the desired signal would be quantized too coarsely.

The assessment of this effect depends significantly on the specific implementation of the AGC. It makes a great difference, if e.g. the signal power is measured before or after A/D-conversion. After A/D-conversion, high amplitude pulses are already hard limited which helps significantly reducing the effect on the AGC. For potential terminals which are designed for the frequency band around 2.8 GHz it can be assumed that the power measurements are done after A/D-conversion, thus taking advantage of a hard limiter. A standard AGC structure is shown in Fig. 30.

FIGURE 30

Standard AGC structure



The received signals in *I*- and *Q*-component are quantized and limited separately resulting in complex samples *zk* = *zIk* + *jzQk*. From these, the power is estimated from the squared amplitudes |*zk*|2. In order to get less noisy estimates of the signal power, the samples are averaged over several µs which helps to reduce the effect of short pulses on the AGC even further. The exact way of averaging is implementation dependent.

Figure 29c shows the result after passing |*zk*|2 through a 1st order recursive filter with a time constant of 60 µs. The thin represents the same estimates but without the interfering radar pulse. The difference between the thick line and the thin line is therefore the estimation error due to the radar pulse. It can be seen that this is less than 1 dB.

For a gliding averaging process the estimation error can be assessed analytically. Assuming a radar pulse within the averaging window with peak amplitude A_{max} in *I*- and *Q*-component separately, the expectation value of the power estimate is given by:

$$E\left[\sum |z|^2\right] = \sigma_z^2\left(1+\frac{T_{pulse}}{T_{av}}\left(\frac{2A_{max}^2}{\sigma_z^2}-1\right)\right) = 2\sigma_I^2\left(1+\frac{T_{pulse}}{T_{av}}\left(\frac{2A_{max}^2}{\sigma_I^2}-1\right)\right)$$

where:

$\sigma_z^2 = \sigma_I^2 + \sigma_Q^2$ power of the desired signal (with $\sigma_I^2 = \sigma_Q^2$)

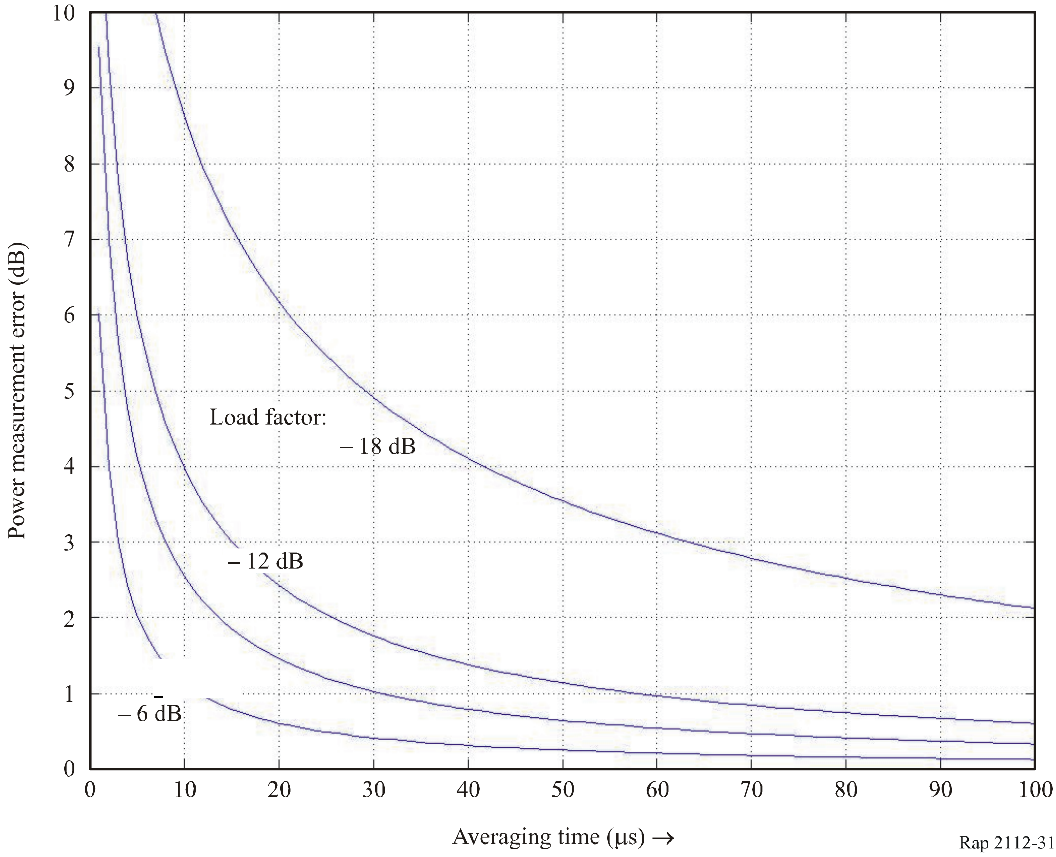
T_{pulse}: pulse duration of the radar pulse

T_{av}: length of the averaging window.

The estimation bias from the radar pulse is given by the second term. For a 1 µs radar pulse this estimation error is shown in Fig. 32 for various load factors.

FIGURE 31

Power measurement error versus averaging time



A measurement error of less than 0.5 dB can be considered as practically not relevant. In other words, if the load factor of the A/D-converter is –9.5 dB and the filter averaging time is 60 µs or more, there is essentially no effect from radar pulses on the AGC. For shorter averaging times there is a small effect which, however, vanishes quickly.

For controlling fast fading effects an averaging time of 60 µs is not too long. This would still allow to follow Doppler frequencies of 1 kHz, corresponding to a vehicle speed of 385 km/h.

The conclusion from these considerations is: It should be no problem to design the AGC such that the effect of radar pulses is negligible.

II Long radar pulses

1 Introduction

In the preceding sections the interference of short radar pulses on the IMT-2000 downlink was analysed with the conclusion that the effects to IMT-2000/WCDMA are negligible, even in the co-channel case. In this contribution also long radar pulses up to 89 µs are considered. Comprehensive simulation results are presented for short as well as for long radar pulses for different frequency separations and different WCDMA spreading factors. From these results protection requirements for IMT-2000/WCDMA can be obtained.

2 Review of interference mechanism

The basic interference mechanism of a radar system to a WCDMA receiver is considered in the preceding section on short radar pulse. It is characterized by the following properties:

Pulsed interference with low duty cycles. Most of the time a WCDMA signal is not interfered at all. The signal is only affected for the duration of the pulses.

High pulse amplitudes are hard limited through the ADC in the WCDMA receiver. The effective signal to radar pulse peak power ratio SRR after the ADC is therefore limited as well and will be between –6 dB and –12 dB, where –12 dB can be considered as the most pessimistic assumption.

Data symbols that are fully interfered (i.e. in 100% of the time) can result in a bit error ratio of up to 50%.

Data symbols which are only fractionally interfered benefit from the fact that the interference power after despreading is proportional to $SF \cdot f$, while the power of the desired signal is proportional to $SF^2(1 - f)^2$where $0 \leq f \leq 1$ is the interfered fraction of the symbol and SF is the spreading factor. The signal-to-noise ratio after despreading is therefore proportional to $SF(1 - f)_2/f$. If e.g. half of the symbol is interfered ($f = 0.5$), the SRR is enhanced by half the spreading factor. Since SRR > –15 dB, the BER can be expected to be much lower than 50% for high spreading factors and $f < 0.5$.

3 Radar characteristics

Radar systems operating in the band 2.7-2.9 GHz can emit pulses with a length ranging from 0.6 µs to 89 µs. Detailed characteristic data can be found in [Proakis, 1995a]. In Table 29 the most important characteristics are summarised. For those radar systems where no rise and fall times are specified in [Proakis, 1995a], assumptions are taken for the simulations which are indicated by numbers in square brackets.

TABLE 30

Characteristics of aeronautical radionavigation/meteorological radars in the band 2 700-2 900 MHz

Characteristics	Radar A	Radar B	Radar C	Radar D	Radar E	Radar F	Radar G
Platform type (airborne, shipborne, ground)	Ground, ATC					Ground, weather	Ground, weather
Tx power into antenna	1.4 MW	1.32 MW	25 kW	450 kW	22 kW	500 kW	400 or 556 kW
Pulse width (µs)	0.6	1.03	Short: 1.0 Long: 89	1.0	Short: 1.0 Long: 5.0	Short: 1.6 Long: 4.7	Short: 1.0 Long: 4.0
Pulse rise/fall time (µs)	0.15-0.2	0.15	Short: 0.5/0.32 Long: 0.7/1	0.15	0.15	0.12	0.15
Pulse repetition rate (pps)	973-1 040 (selectable)	1 059-1 172	Short: 722-935 Long: 788-1 050	1 050	1 031 to 1 080	Short: 318-1 304 Long: 318-452	Short: 539 Long: 162
Duty cycle (%)	0.07 maximum	0.14 maximum	9.34 maximum	0.1 maximum	5.94 maximum	0.21 maximum	

WCDMA is based on a spread spectrum air interface with a chip-rate of 3.84 Mchip/s [Proakis, 1995b]. The spreading factor can be selected as a power of 2 between 8 and 512 in the downlink, giving symbol lengths between 2.033 μs and 133 μs.

4 The simulation model

In order to assess the interference rejection capabilities of a WCDMA receiver, a simulation model has been set-up. Random data is channel encoded, mapped to a dedicated physical downlink channel, multiplexed with a dedicated control channel and finally modulated and spread according to the 3GPP specifications [Proakis, 1995b]. For the simulations presented here, the channel is a static additive white Gaussian noise (AWGN) channel with a sufficiently high SNR such that symbol errors occur only from radar interference.

The radar interference is generated by a trapezoidal pulse generator. This signal can optionally be shifted in frequency by multiplying with $\exp(j2\pi t\Delta f)$ where Δf is the frequency offset between the center frequencies of the WCDMA-signal and the radar signal.

The additive superposition of the desired signal, the noise and the radar signal is then passed through the channel filter. This is modelled as an 8^{th} order Butterworth filter with a 3 dB bandwidth of 3.84 MHz.

The filtered signal is then passed through a fast AGC loop which includes the ADC. The AGC is able to follow fast fading, such that its load factor is around –6 dB (= ratio of the input power to the square of the ADC amplitude limit).

The quantized signal is then fed into the signal processing unit, where all necessary receiver tasks are done like channel estimation, time synchronisation, despreading and symbol estimation.

The detected binary data are then compared with the transmitted data to obtain the raw bit error ratio (rawBER). For selected simulations, also channel encoding and decoding is included to see the effect on the user data.

The parameters of the simulation blocks are chosen such that all possible time and phase relations between the radar signal and the wanted signal occur with equal probability.

5 Simulation results

Co-channel interference

The results for co-channel interference for some selected spreading factors are shown in Fig. 32 to 34. They show BER versus SRR (= signal to radar peak power ratio at the input of the receiver, i.e., before filtering).

The long radar pulses from radars C and E have a significant higher raw BER than the short pulses. Its pulse length is higher than the longest WCDMA symbol length with the consequence that each pulse affects several consecutive symbols. In this case, the theoretical maximal error rate is essentially determined by the duty cycle of the radar signal. The maximum bit error ratio during the reception of the radar pulse is 50% (for high radar peak power), which gives a total error ratio of about 0.5*d, where d is the duty cycle. For radar C this gives BER_{max} = 4.7% and for radar E we have BER_{max} = 3%. In the simulation these values are slightly exceeded which can be explained with the pulse broadening effect described below.

The shorter radar pulses cause much less errors. Except from the long pulses of radars F and G all other pulses are shorter than the shortest symbol length in WCDMA, i.e. only one symbol per radar period is affected. The theoretical upper limit of the raw BER can be estimated to $\frac{1}{2} \cdot T_S \cdot PRR$ where T_S is the symbol length and PRR is the pulse repetition rate. One would expect the curves to approach this limit, which is obviously not the case. The reason for the increase of raw BER with decreasing SRR is the IF-filter in the WCDMA receiver, which broadens the foot of the pulse. For a given SRR-value the effective pulse width is roughly the width of the pulse at this level. Figure 45 shows as an example the filtered pulse of radar B which has a width of nearly 10 µs at SRR = –100 dB. Within these 10 µs the effective signal to interference ratio is below 0 dB.

Looking at the curves for the shorter pulses (lower part in Figs. 32 to 34) it can be observed that the raw BER can differ by a factor of 7 (compare G_long with F_short). This can be be explained with the different pulse repetition periods (PRR) which have the dominating effect on raw BER. This explains also why the long pulses of radar F have lower error ratios than the short ones.

FIGURE 32

Raw BER versus SRR for co-channel interference and WCDMA spreading factor 8

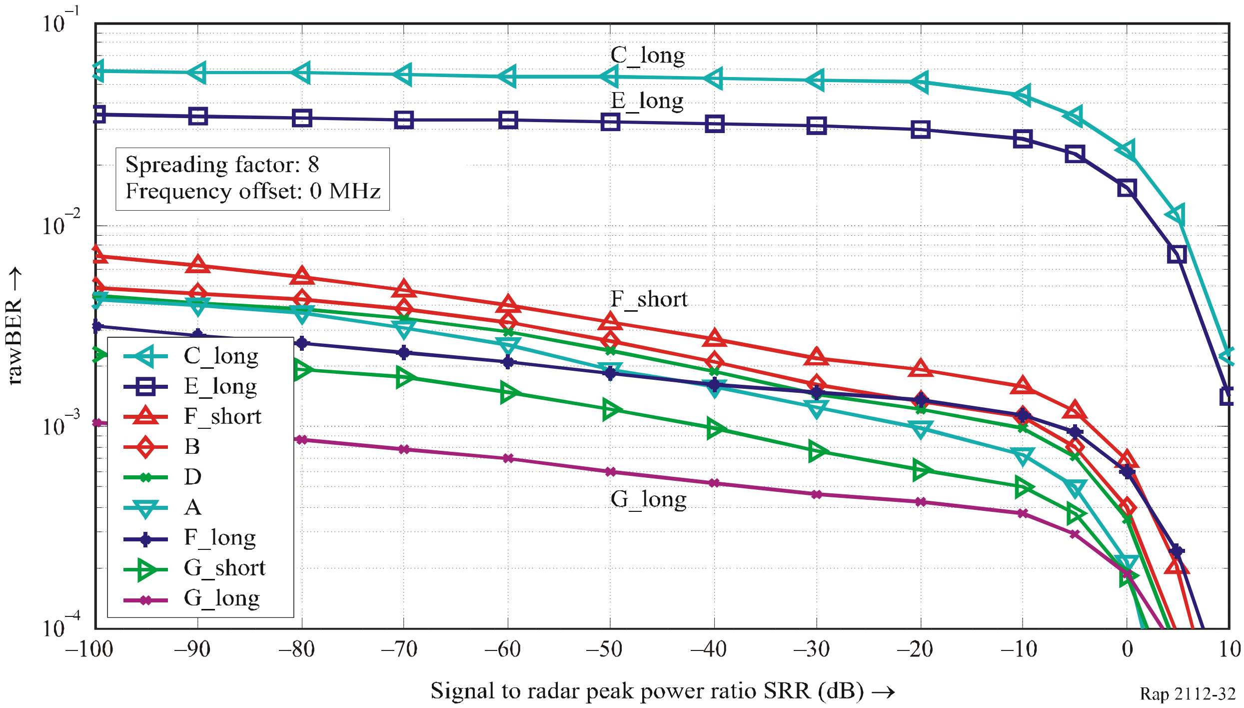


FIGURE 33

Raw BER versus SRR for co-channel interference and WCDMA spreading factor 32

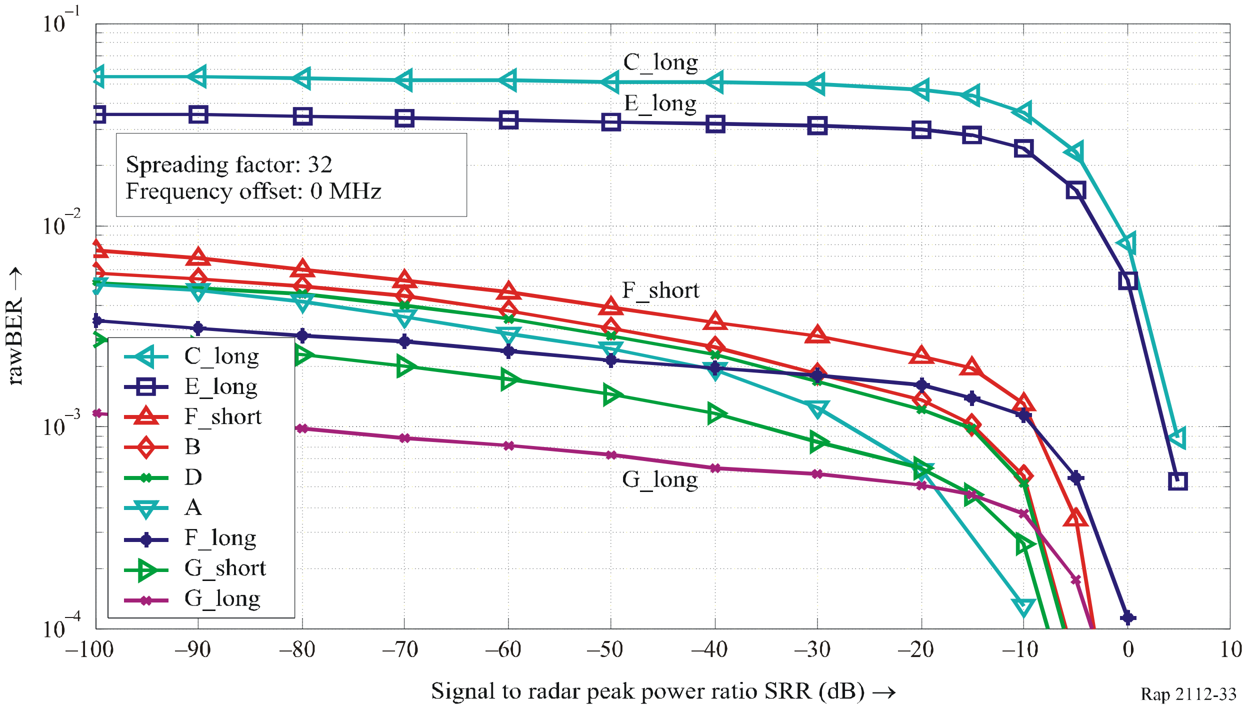
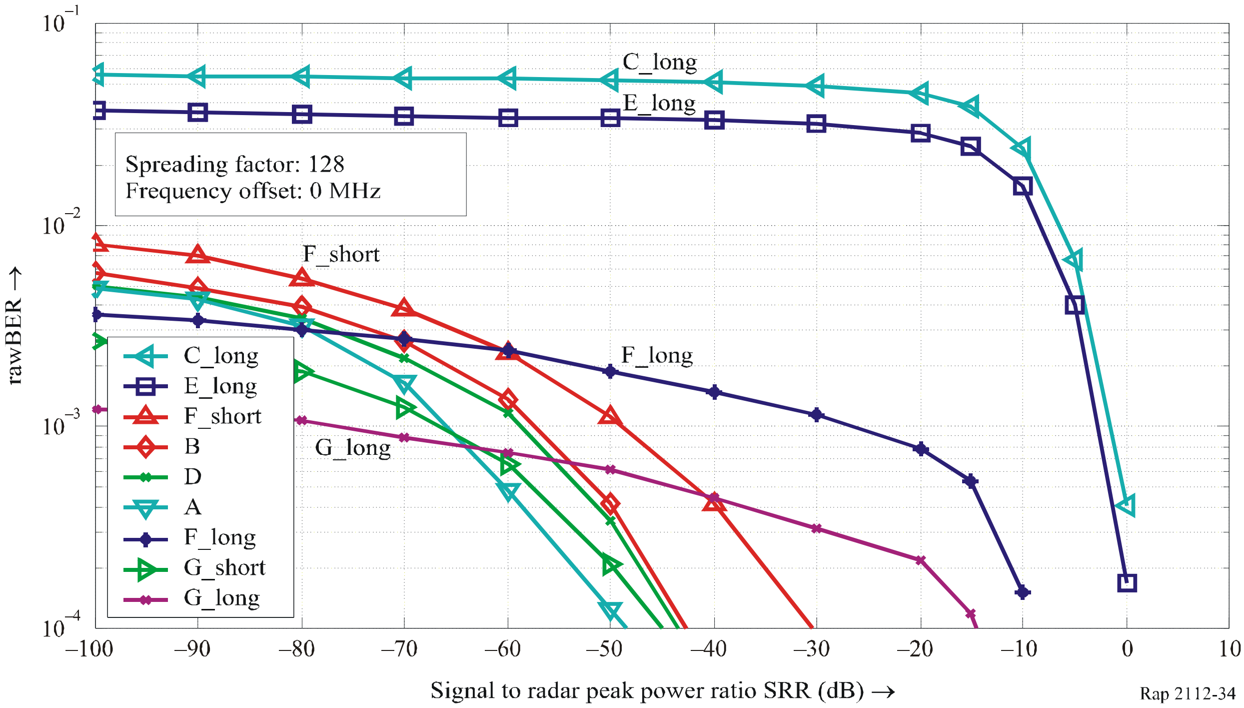


FIGURE 34

Raw BER versus SRR for co-channel interference and WCDMA spreading factor 128



Adjacent channel interference with 5 MHz offset

Figures 35 to 37 show results for the case that the WCDMA receive frequency is 5 MHz offset from the radar transmit frequency. Results for 3 long pulses and one short pulse (radar B) are shown.

At 5 MHz offset there is no significant difference between short and long pulses anymore. The reason lies again in the WCDMA IF-filter which has a differentiating effect on the pulses with the consequence that mainly the shape of the rising and falling slopes determine the effects on the WCDMA receiver, irrespective how long the pulse really is. This is illustrated in Fig. 46, which shows how the IF-filter of a WCDMA-receiver affects the long pulse of radar E with 0, 5 and 20 MHz frequency offset. Mainly the small spikes at the pulse edges determine the effect on BER. At 5 MHz offset the center part of the pulse has still a high level. The falling slope of the center part is due to the chirp modulation which was assumed to be linear from low to high frequencies. Although the modulation in reality might be different, this will not have a significant effect on the simulation results.

It is worth noting that also the long radar pulses have now error rates below 1% for reasonable SRR-values. In none of all simulated cases errors could be observed after channel decoding.

FIGURE 35

Raw BER versus SRR for 5 MHz frequency offset and WCDMA spreading factor 8

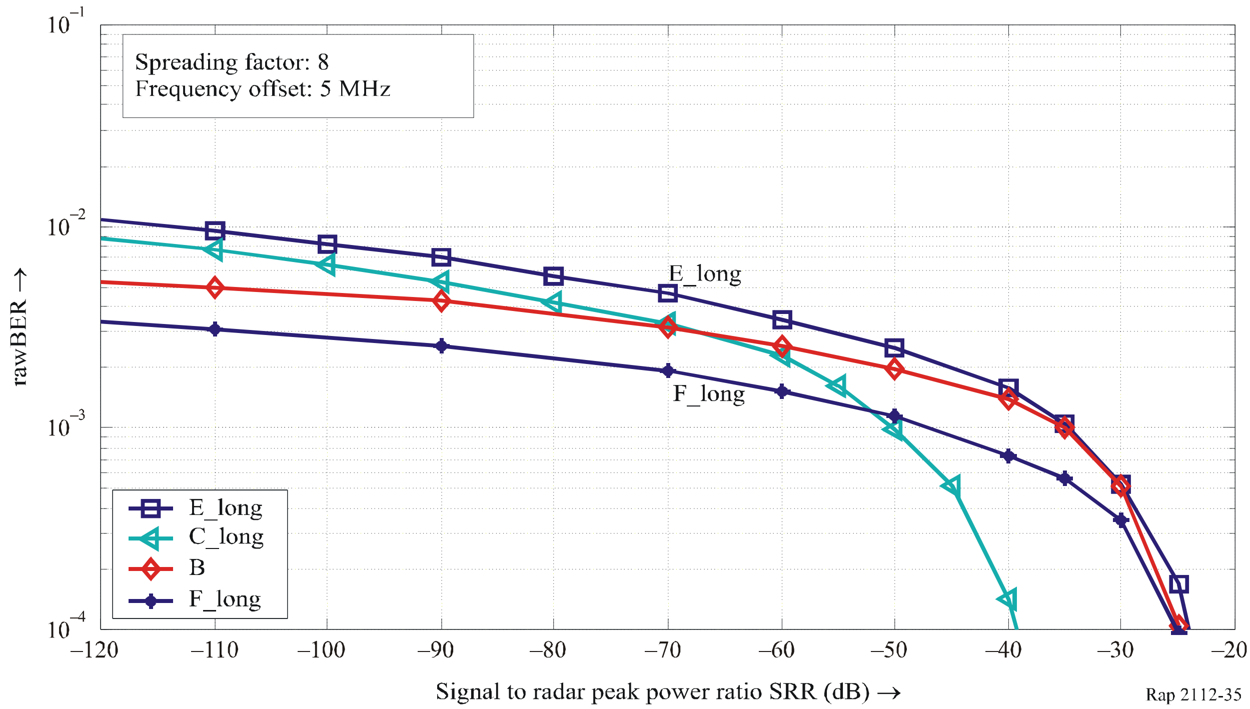


FIGURE 36

Raw BER versus SRR for 5 MHz frequency offset and WCDMA spreading factor 32

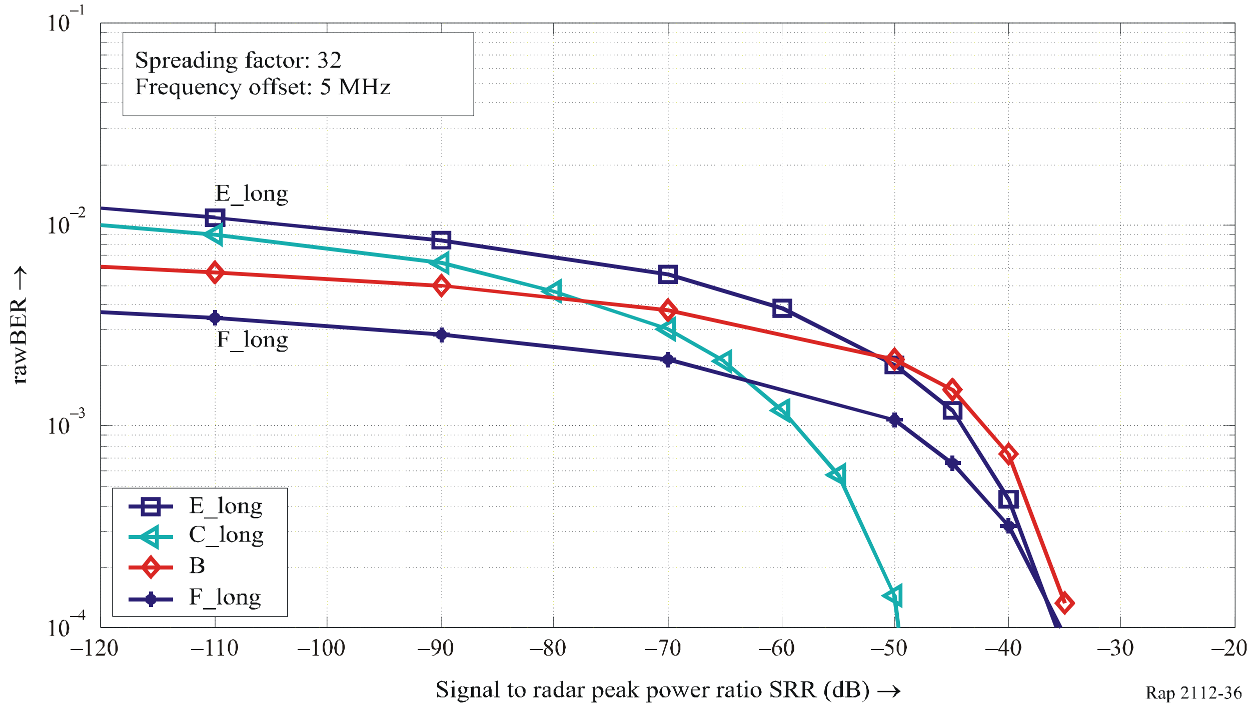
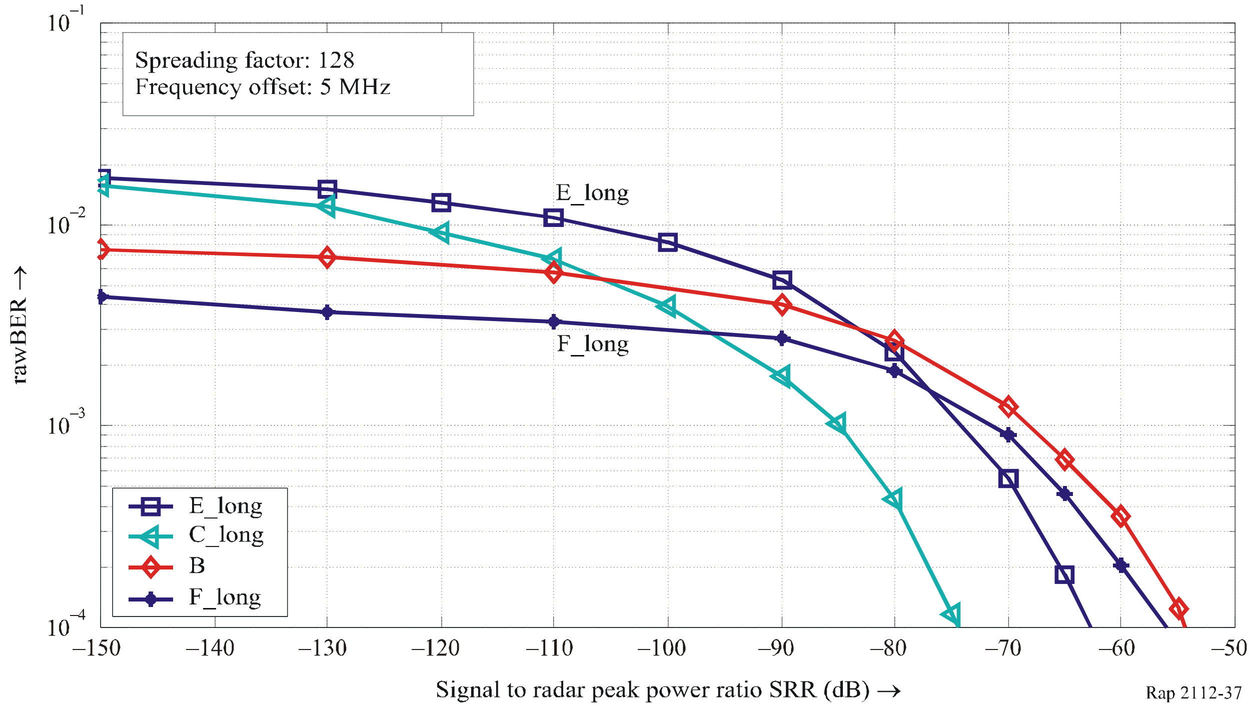


FIGURE 37

Raw BER versus SRR for 5 MHz frequency offset and WCDMA spreading factor 128



Adjacent channel interference with 10 and 20 MHz offset

Figures 38 to 40 show results for the case that the WCDMA receive frequency is 10 MHz offset from the radar transmit frequency. Results for 3 long pulses and one short pulse (radar B) are shown.

Compared to 5 MHz offset the curves are very similar, but shifted by 15-18 dB (depending on the pulse shape) to the left.

An offset of 20 MHz gives essentially the same curves but with an additional attenuation gain. Compared with 5 MHz offset, the curves are shifted by 25-33 dB depending on the spreading factor and the pulse shape (28-30 dB for C_long, 30 dB for E_long, 25-30 dB for F_long and 32 dB for B).

FIGURE 38

Raw BER versus SRR for 10 MHz frequency offset and WCDMA spreading factor 8

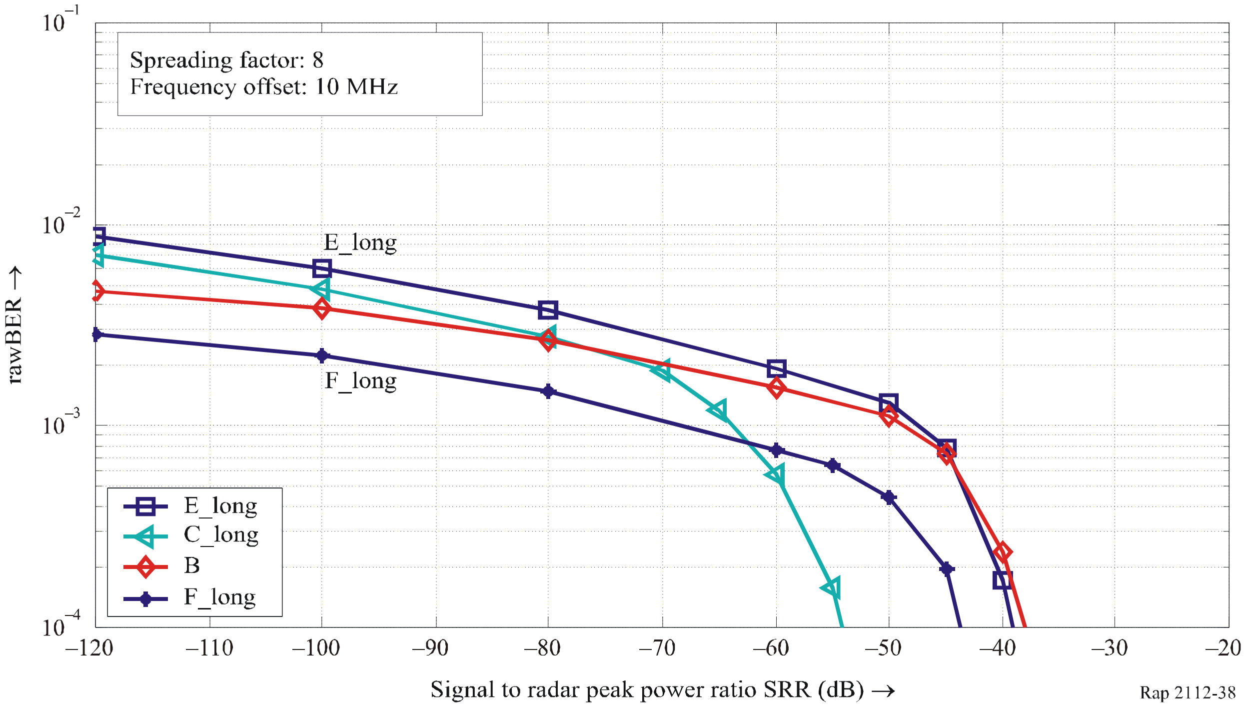


FIGURE 39

Raw BER versus SRR for 10 MHz frequency offset and WCDMA spreading factor 32

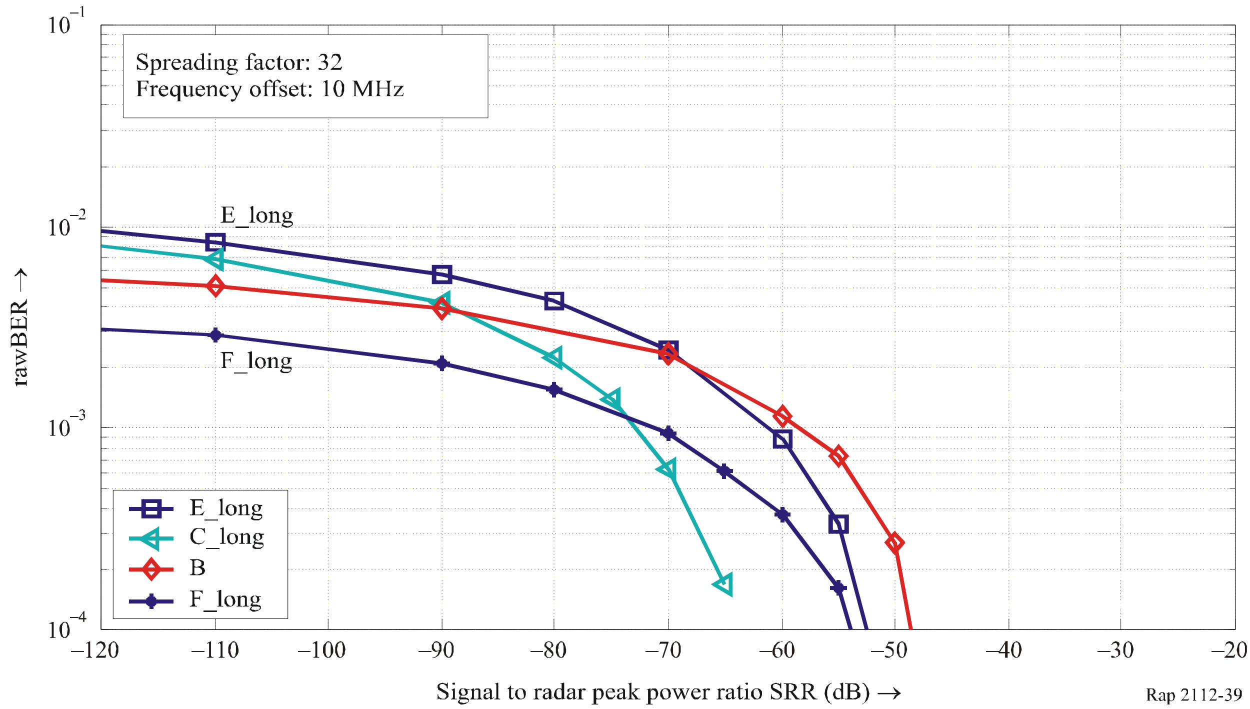


FIGURE 40

Raw BER versus SRR for 10 MHz frequency offset and WCDMA spreading factor 128

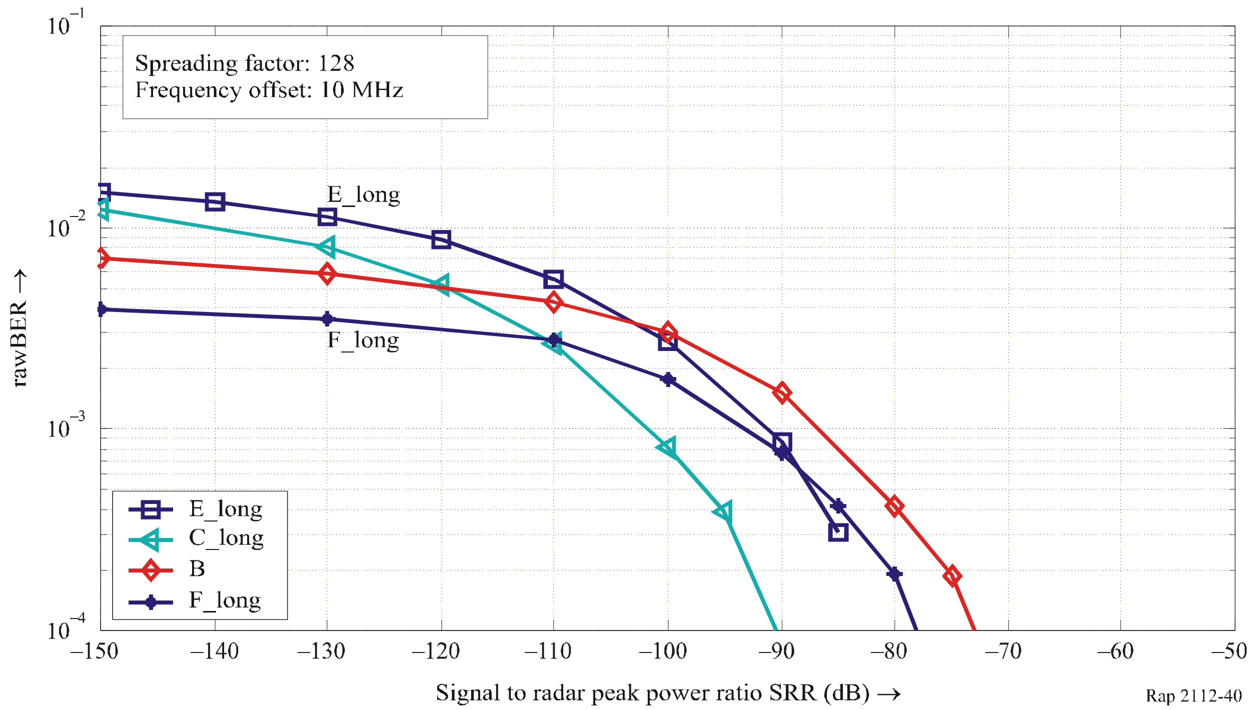


FIGURE 41

Raw BER versus SRR for 20 MHz frequency offset and WCDMA spreading factor 8

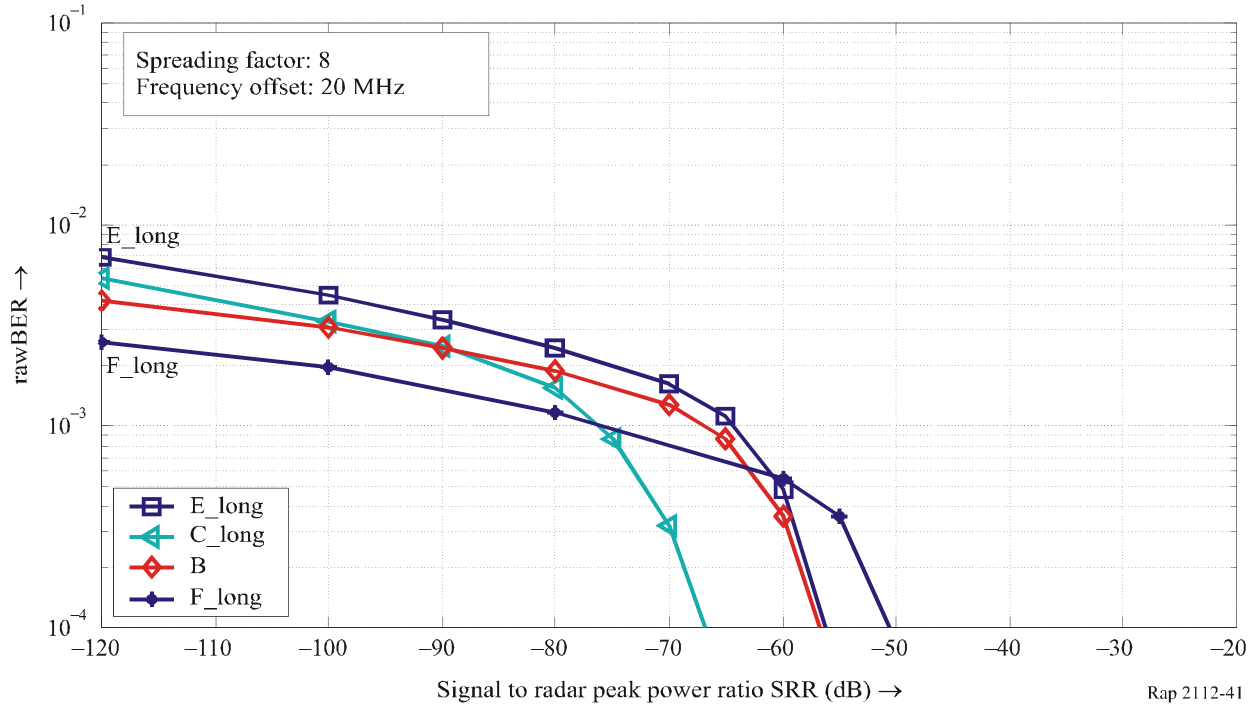


FIGURE 42

Raw BER versus SRR for 20 MHz frequency offset and WCDMA spreading factor 32

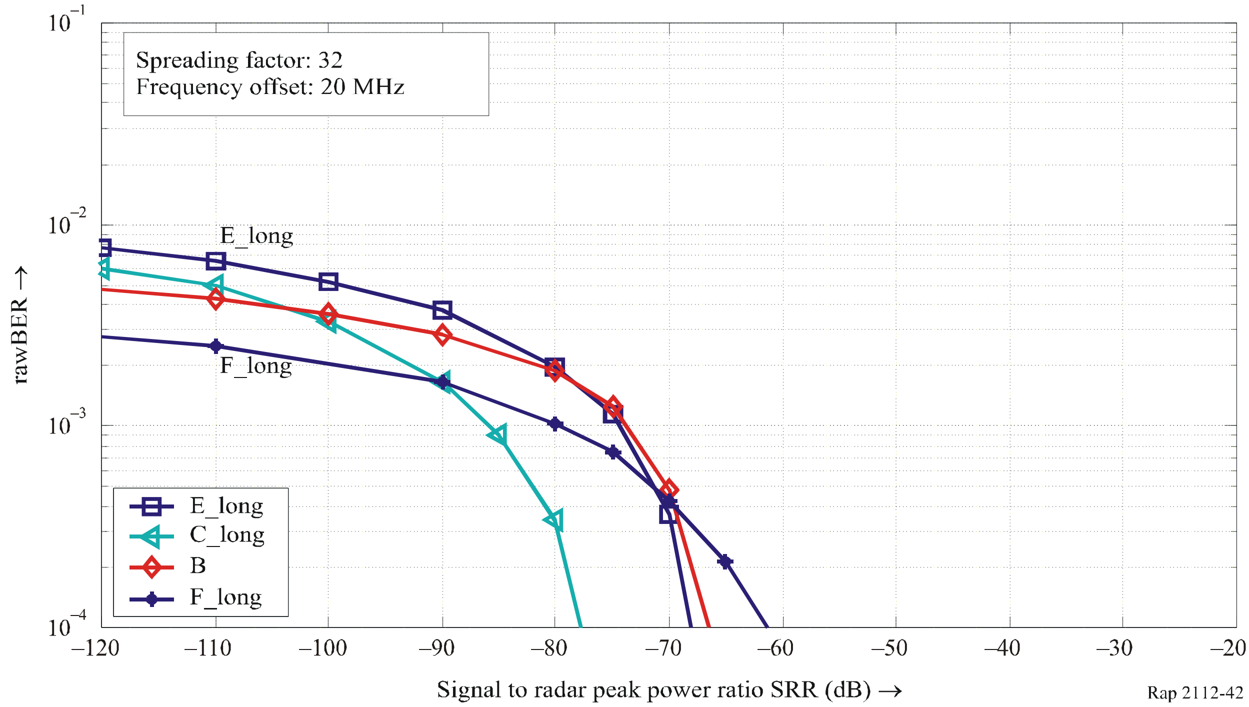


FIGURE 43

Raw BER versus SRR for 20 MHz frequency offset and WCDMA spreading factor 128

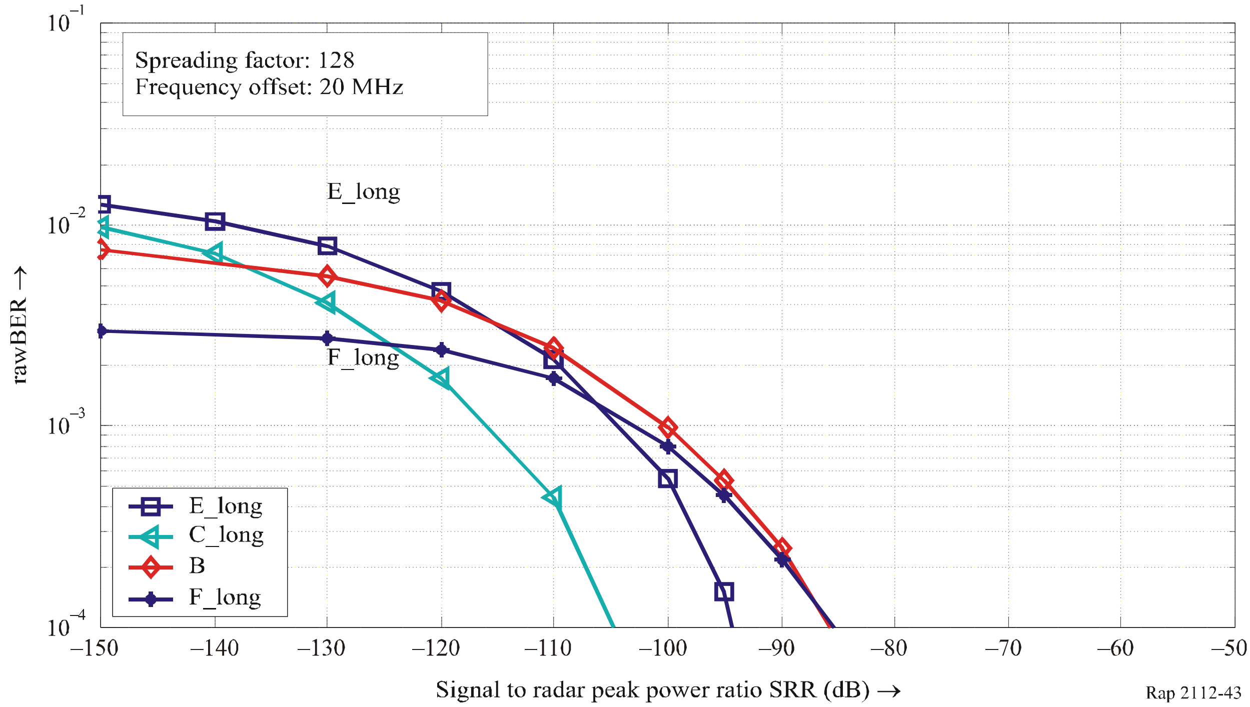


FIGURE 44

Envelope of the filtered pulse of radar B

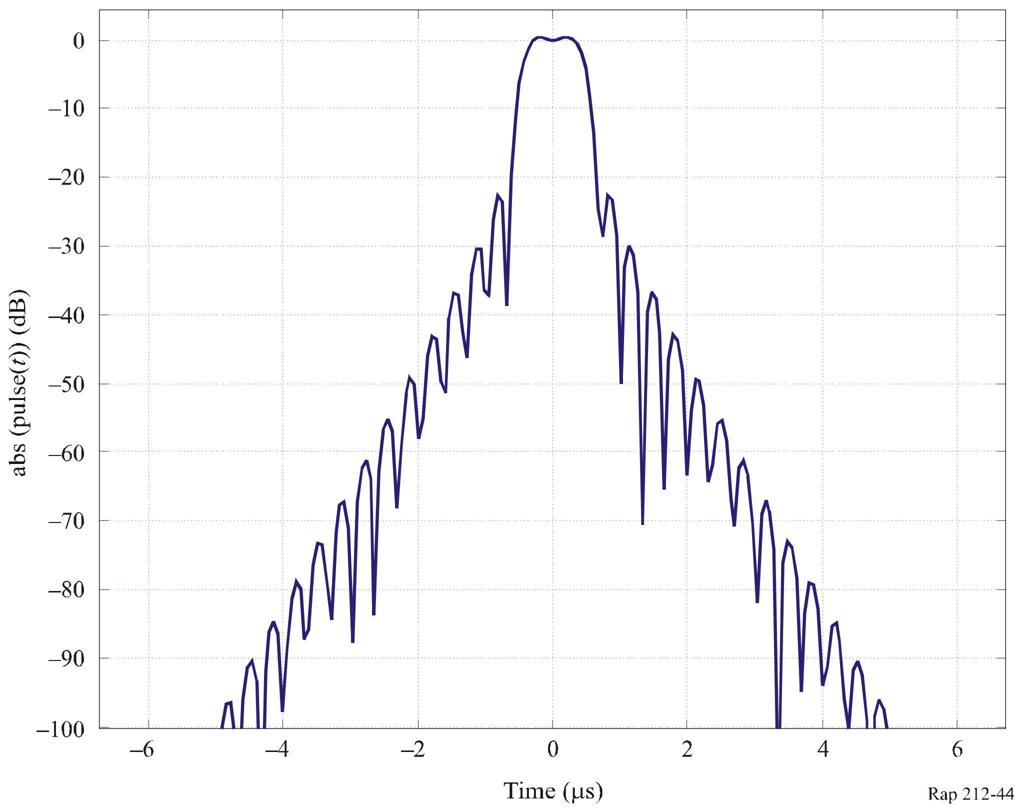
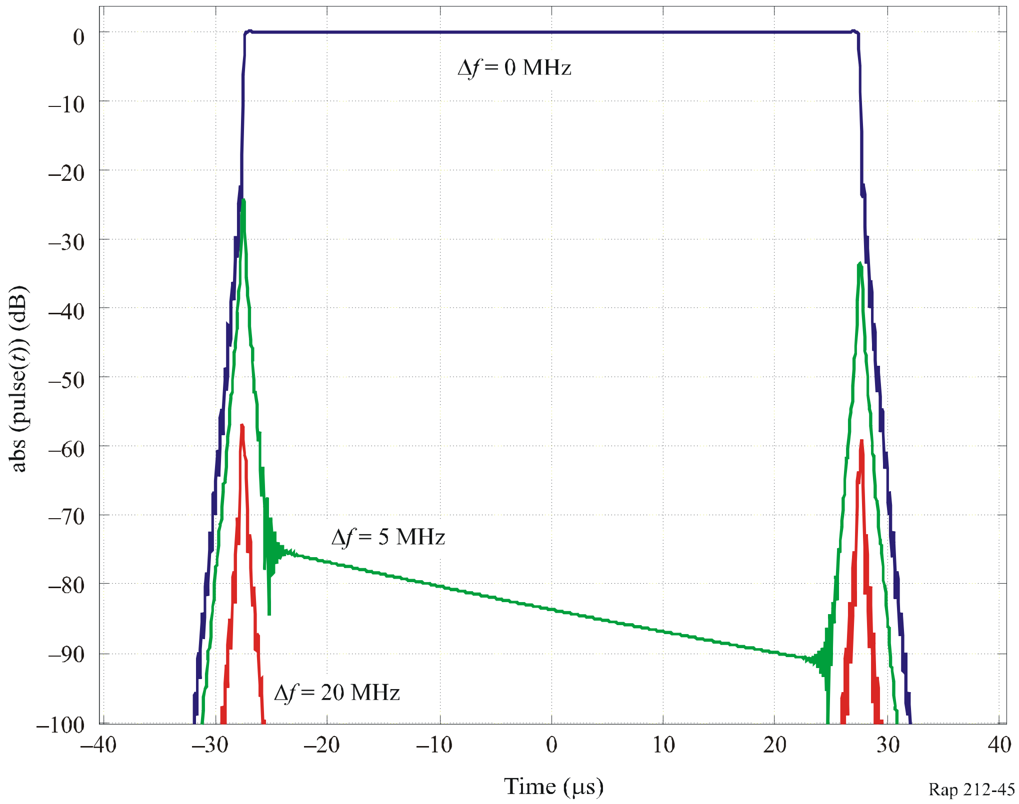


FIGURE 45

Envelope of filtered pulses of radar E (long) with different frequency offsets



In order to draw some conclusions from the simulation results, it is necessary to assess the effect of radar interference to a WCDMA-link in the presence of other interference like Gaussian noise. Figure 46 shows the raw BER versus the E_s/N_0 for a static AWGN channel for three types of radar interference:

No radar with very high peak power.

Radar of type C with long pulses in the co-channel case with very high peak power (100 dB above signal level); this is the worst case.

Radar of type E with long pulses for a frequency offset of 5 MHz with very high peak power (110 dB above signal level).

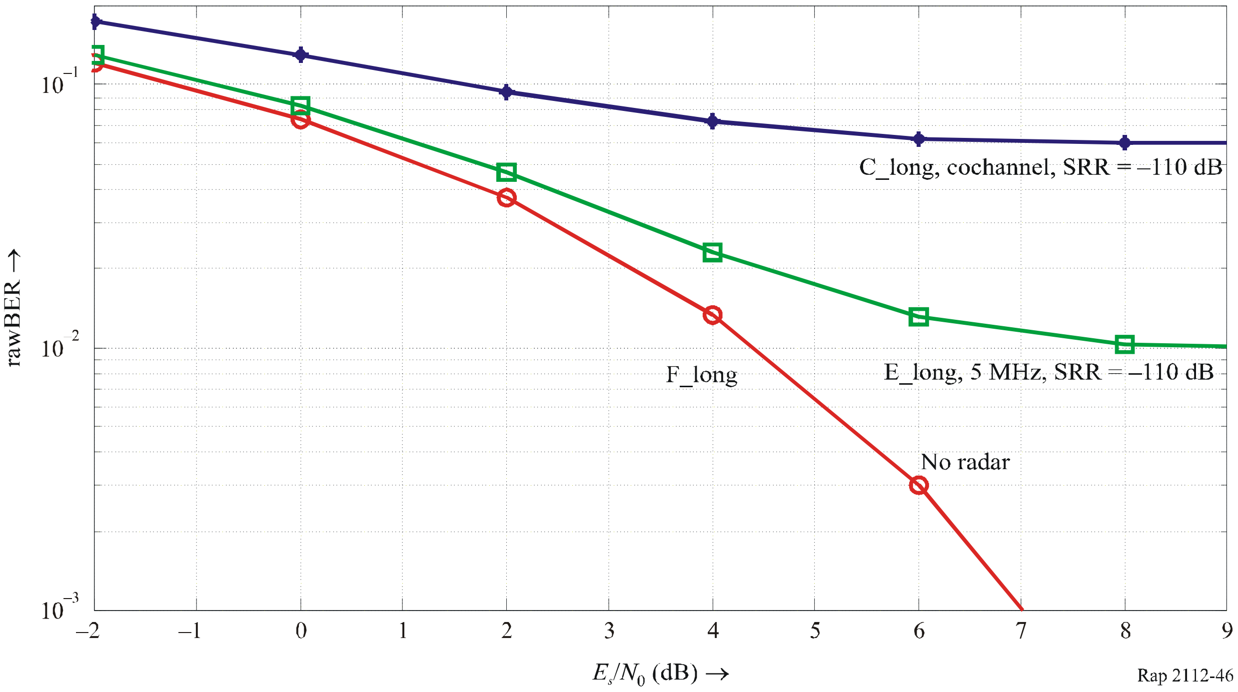
The BER-level of interest is in the order of 8%. With up to 8% random errors, nearly all errors can be corrected by the powerful channel coding scheme in WCDMA. Therefore it is reasonable to take the 8% as a basis for the degradation assessment.

At this level, the degradation from co-channel interference from radar C is in the order of 4 dB. Although an operation of WCDMA would still be possible, this degradation should be avoided.

The degradation from adjacent channel interference of radar E is in the order of 0.2 dB which can be considered as negligible. Since radar E is the worst case for frequency offset of 5 MHz and higher, it can be concluded, that adjacent channel operation of a WCDMA downlink is possible, even for high received radar power (e.g. 110 dB above WCDMA signal level).

FIGURE 46

Raw BER versus E_s/N_0 for selected radar interferers



It must be emphasized that the assumption behind these results is that the peak power for each radar pulse is the same. When assessing the true effect of radar interference to the BER the rotation of the radar antenna must be taken into account. The high peak power is only present during the time the main beam of the radar antenna hits the WCDMA receiver which lasts typically no longer than a few milliseconds. The rest of the rotation cycle (typically several seconds) the peak power is several 10 dB lower.

6 Conclusions

The simulation results presented above allows to extend the statement given in [Meyr and Ascheid, 1990] for short radar pulses to long pulses:

For short radar pulses there is no fundamental limit in the robustness of a WCDMA receiver against radar interference. The reason lies in the fact that each receiver has an AD-converter combined with an AGC which limits the amplitude of radar pulses. The error ratio is limited by the low duty cycle of the radar signal. This conclusion also applies for the long radar pulses of type F and G with their low pulse repetition rate.

For long pulses of radar type C and E a frequency separation is required. The results indicate that a separation of 5 MHz is already sufficient. The question of the maximum tolerable level of the received peak power in this case needs special consideration: From the simulations it could be concluded that the radar peak power can be 110 dB and more above the received signal level. For long pulses of radar type C and E, however, there is a limit which is given by receiver blocking level. (Blocking was not considered in the simulations.) In the simulations the filtered radar pulse is the only source of interference. In case of a frequency offset this filtered pulse consists essentially of two spikes at the edges of the unfiltered pulse. Between these two pulses there is basically no interference after the IF-filter. But the radar signal is still present at the receiver front-end which might cause a significant sensitivity degradation (blocking effect). The blocking level should therefore not be exceeded.

The results establish the general robustness of mobile radio communication systems against pulsed interferers. This is in line with results from measurements with GSM and NMT equipment carried out several years ago.

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