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ANALYSIS AND MITIGATION OF WLAN INTERFERENCES

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1 INTRODUCTION

Interference of WLAN networks compliant to the IEEE 802.11h standard (1) with C-Band weather radar systems is an increasing problem in Europe. The spectral compliance of these networks is specified by the EN 301893 standard (2). Although the standard requires that dynamic frequency selection (DFS) must be applied by the networks in order to avoid interference the realization of this requirement seems to be much more difficult than expected. Examples are provided in (3), (4), (5). This paper presents the analysis of a typical interference situation and discusses consequences for the operation of the DFS. A possible frequency management strategy is suggested. A receiver design is presented which allows the mitigation of WLAN interferences to a high degree.

2 LEGISLATIVE REGULATIONS

In the European Union (EU) the Radio and Telecommunications Terminal Equipment (R&TTE) Directive (6) constitutes the basis for the national radiofrequency spectrum management legislative of the member states. The technical and the testing requirements for WLAN devices according to IEEE 802.11h are laid down in the European Norm EN 301893. Any WLAN devices sold in the EU must comply to these requirements. The compliance is confirmed by the CE mark.

2.1 Technical Requirements

The technical requirements as defined by EN 301893 and IEEE 802.11h are summarized below for the frequency band 5470 MHz to 5725 MHz. The most important feature with respect to radar interference mitigation is Dynamic Frequency Selection (DFS). Functions and figures used by the EN for the specification of the DFS operation are set off by bold letters.

The EN distinguishes between “master devices” (MD) and “slave devices” (SD). In the technical realization an MD is an access point, such as a WLAN router. An SD is a WLAN board in a PC or a notebook. MDs must use Radar Interference Detection (RID) as part of the DFS functionality. SDs must also use RID if the **mean EIRP density limit** is exceeded. When a WLAN is established all channels must be designated as **unavailable channel**. Before an MD allocates channels in a network it must perform a channel availability check (CAC) during the **channel availability check time**. If a radar signal is detected which exceeds the **interference threshold** the respective channel is blocked for the **non-occupancy period**. During operation the MD must monitor the **operating channel** by means of an **in-service monitoring** (ISM) function for radar signals. The EN does not specify how ISM must work but it provides a test specification for this function. If a radar is detected the MD must change the channel within the **channel move time**. SDs are not allowed to transmit before being enabled by an MD. There is one exception however. Some WLAN interfaces are capable to operate in an ad-hoc mode without being connected to an MD. Such devices must operate with DFS. Some of the technical requirements defined by the EN are listed in Table 1 and Table 2.

Mean EIRP density limit	17 dBm/MHz
Mean EIRP density limit for SD w/o RID	10 dBm/MHz
interference threshold	-64 dBm (MD EIRP>200 mW)
	-62 dBm (MD EIRP<200 mW)

Table 1: MD and SD Requirements

channel availability check time	60 s
non-occupancy period	30 min
CAC repetition period	24 h min
Channel move time	10 s

Table 2: DFS Requirements

Detailed specifications about the utilization of the spectrum allocated by the EN can be found in IEEE 802.11h (1). The channel designation is listed in Table 3.

Channel No	100	104	108	112
Frequency [MHz]	5500	5520	5540	5560
Channel No	116	120	124	128
Frequency [MHz]	5580	5600	5620	5640
Channel No	132	136	140	
Frequency [MHz]	5660	5680	5700	

Table 3: WLAN Channel Allocation

IEEE 802.11a (7) provides the channel spectrum mask. The bandwidth of a channel is 20 MHz which is much less than the maximum bandwidth of 40 MHz allowed by the EN.

3 INTERFERENCE-TO-NOISE RATIO

The radio link budget for undisturbed radio communication links is calculated with the Friis equation (8). This equation is modified in order to estimate the interference to noise ratio (INR) received by the radar. The INR describes the degree by which the interference power level exceeds the thermal noise. The WLAN device is considered by using its Equivalent Isotropically Radiated Power Density EIRPD:

$$INR = \frac{P_r}{N} = \left(\frac{c}{4\pi}\right)^2 \frac{EIRPD \cdot B_{MF} \cdot G_R \cdot G_c}{(r \cdot f)^2} \cdot \frac{1}{k_B \cdot T \cdot B_{MF} \cdot N}$$

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The interfering power level is determined by the Matched Filter bandwidth B_{MF}. Since the WLAN signal is probably not received through the main lobe but through a side lobe the radar antenna gain G_R must be reduced by the gain compression G_C of the respective side lobe. The distance between the WLAN transmitter and the radar is r and the radar has the frequency f. The thermal noise power density is determined by k_BT and multiplied by the noise figure N of the radar receiver. Since most of the relevant figures are normally provided in dB, a link budget in logarithmic terms is useful. The logarithmic link budget together with some typical radar data as example are provided in Table 4. B_{MF} is not considered any more because it is cancelled out.

Variable	Figure	Figure in dB	dB Normalization
$[c/(4\pi)]^2$	$5.69 \cdot 10^{14}$ m^2/s^2	+147.55	$dB(m^2/s^2)$
EIRPD		+17	dBm/MHz
G_R		+45	dB
G_c		-27	dB
$1/r^2$	20 km	-2*13	dBkm
$1/f^2$	5640 MHz	-2*37.51	dBMHz
$1/(k_BT)$	T=300K	+113.83	dBm/MHz
1/N		-2	dB
Magnitudes		-180	
INR		**13.36**	**dB**

Table 4: INR Budget Calculation

It can be seen that under the conditions assumed in the example above the radar will be disturbed by the WLAN. Even if realistic conditions such as attenuation by walls, obstruction, and the WLAN antenna radiation pattern are applied which might reduce the INR by 10 dB an interference still exists. It must also be considered that the RID function is tested for a probability of detection of only 60%. Frequency management is required to reduce the disturbance of the radar.

4 FREQUENCY MANAGEMENT STRATEGIES

The most effective strategy is the selection of a radar frequency outside of the WLAN band. This is no problem with magnetron transmitters but e.g. klystron transmitters which employ the VKC-8387 tube cannot be tuned outside this band.

The R&TTE Directive defines the radar as a “primary device” since it performs a task which is important for the public safety. WLANs are “secondary devices” which must be deactivated if they interfere with a primary device, even if they are fully compliant to the EN. If a weather service notices an interference it may inform the national frequency management authority which has to take appropriate measures.

If a radar must be operated within the WLAN band the operating service has no chance but to rely on the DFS efficacy of the WLAN devices. There are two possible choices of the radar frequency: between two WLAN channels or on a WLAN channel. Both possibilities are discussed below.

4.1 Radar Band between two WLAN Channels

From Fig. 1 it is clear that the interfering signal power is only reduced by 10dB, if the radar band is positioned between two WLAN bands.

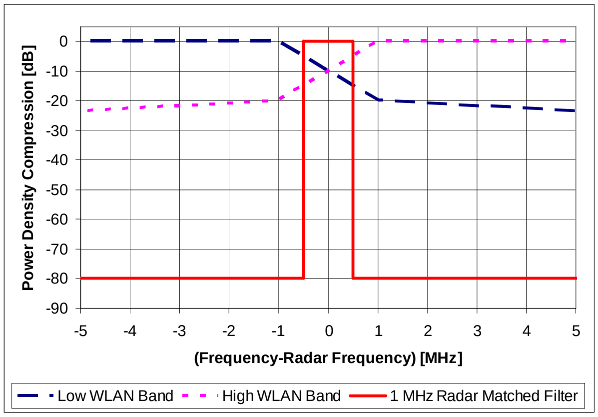

Fig. 1: Radar Band between two WLAN channels

If both WLAN channels would be active, the reduction would only be 7 dB, but this situation is quite unlikely. However it is also unlikely that the RID will detect the radar properly because it is outside of the respective channel. It must also be considered that the noise generated by the WLAN in the radar receiver is not white. Its spectrum depends whether the radar operates on the upper or lower edge of the WLAN channel. A distortion of radar measurements due to the coloured noise is likely.

4.2 Radar Band on an Unavailable WLAN Channel

The situation is quite different if the radar frequency is centered in a WLAN channel. If the WLAN RID works the resulting spectra of the WLAN and the radar should be placed as depicted in Fig. 2.

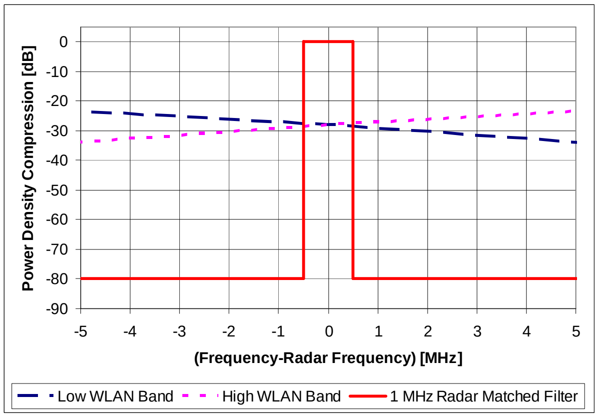

Fig. 2: Radar Band on an unavailable WLAN channel

If the WLAN switches from the channel occupied by the radar to the adjacent channel the interfering signal power is reduced by 28 dB. In most cases this should be sufficient for an interference-free radar operation. However it must be stressed that this approach does only work if the DFS and in particular the RID of the WLAN operates efficiently.

5 RADAR RECEIVER DESIGN

Even if the WLAN DFS tags the radar frequency f_R as unavailable channel and switches to another channel it must be ensured that signals which are not within the radar band, so-called out-of-band signals (OOB signals) do not cause any interference. The most important filter for the rejection of these signals is the Matched Filter of the radar. Therefore the first step to prevent interference from OOB signals is to prevent the mixing of these signals on the intermediate frequency $f_{IF}=f_R-f_{LO}$ of the radar. The IF signal with the amplitude s_{IF} can be calculated from:

$$s_{IF}\cos(2\pi f_{IF}t) = s_{IF}\cos[2\pi(f_R - f_{LO})t]$$

The frequency of the local oscillator is f_{LO}. If a signal with the frequency $f_{IM}= f_R-2f_{IF}$ is received, this signal is converted to

$$\begin{aligned} & s_{IF,IM}\cos\{2\pi[(f_R-2f_{IF})-f_{LO}]t\} = \\ & = s_{IF,IM}\cos\{2\pi[f_{IF}-2f_{IF}]t\} = s_{IF,IM}\cos(2\pi f_{IF}t) \end{aligned}$$

The intermediate frequency of this signal is the same as the IF of the radar signal although the RF frequency was different. This behaviour is a characteristic feature of any mixing process and the characteristic frequency which is mixed to the same IF as the design frequency is called image frequency f_{IM}. It is possible to influence this frequency by choosing either high-side mixing ($f_{LO} > f_R \Rightarrow f_{IM} > f_R$) or low-side mixing ($f_{LO} < f_R \Rightarrow f_{IM} < f_R$) and by the design intermediate frequency. Advanced mixer architectures, so-called image rejection mixers try to cancel the image frequency by proper combining the IF signals of two mixers but the rejection which is achieved by these mixers is only 15-20 dB. This is not sufficient for the rejection of WLAN interferences.

Efficient rejection of image frequencies is only possible by filtering the RF signal. If the radar frequency can be tuned over a wide range the image must be set outside of the tuning range by selection of a suited IF, otherwise the RF filter providing the image rejection must be changed if the radar frequency is changed. For example, if the radar can be tuned from 5400 MHz to 5900 MHz and low-side mixing is selected, the IF must be at least 260 MHz. Then a radar frequency of 5900 MHz would open an image window at 5380 MHz. Another advantage of a large gap between the stop band and the pass band of the RF filter is a low insertion loss.

Another reason for the occurrence of interference is the A/D converter of the digital receiver. The basic problem of all digital receivers is the folding of out-of-band signals into the digital receiving band which is defined by the matched filter. This process is called **aliasing**. It is illustrated in Fig. 3.

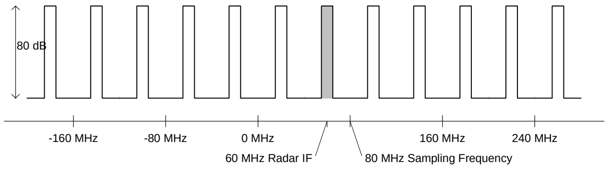

Fig. 3: Aliasing of the digital IF receiver band

The shaded area represents the digital matched filter which defines the bandwidth of the digital receiver. The center frequency f_{IF} of the shaded area resembles the IF provided by the analog receiver, which is 60 MHz in the example. All signals in the unshaded bands will be folded or aliased into the receiver bandwidth. For instance, if there is another signal at 100 MHz it would be received and processed exactly as a signal at 60 MHz. The center frequencies $f_{alias,n}$ of the alias bands can be calculated from:

$$f_{alias,n} = n\cdot f_s \pm (f_s - f_{IF}),\quad n = 0,1,2\ldots$$

f_s is the sampling frequency of the A/D converter, which is 80 MHz or 80 MS/s in our example. If the radar frequency is 5640 MHz, a signal at 5680 MHz could not be distinguished from the radar backscatter without further measures.

5.1 *Anti-Alias Filtering*

The usual approach to suppress image signals is the insertion of an anti-alias filter at the output of the analog receiver. The characteristics of such a filter is sketched in Fig. 2

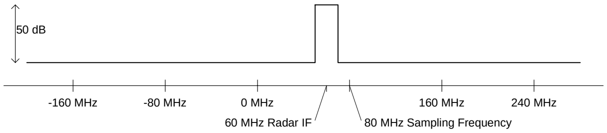

Fig. 4: anti-alias filter characteristics

The combined response from the matched filter and the anti-alias filter is shown in Fig. 3.

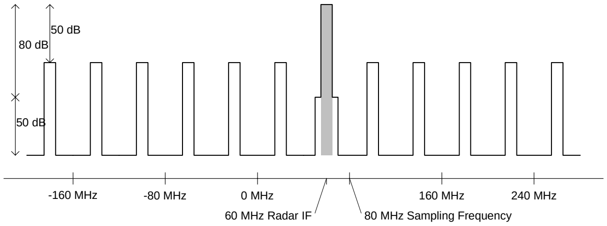

Fig. 5: Combined response of matched and anti-alias filter

By cascading several anti-alias filter nearly all signals in the alias bands can be suppressed beyond the noise level. However, since the alias filters have a relatively low center frequency they must be realized with discrete components. This limits their high-frequency rejection capability. Because modern A/D converters have a quite high bandwidth it is possible that alias signals at high frequencies may still leak into the digital receiver.

5.2 *Dual-conversion Technique*

In order to keep the noise figure of the A/D conversion as low as possible a relatively low IF should be sampled. On the other hand, a high IF is required for proper image rejection. Both requirements can be satisfied by a dual-conversion receiver featuring two intermediate frequencies, a high and a low frequency. The high IF is also selected in order to allow the realization of narrow bandpass filters with high rejection over a wide band and low insertion losses, which is another advantage of this design. UHF frequencies are a good choice. The combined response of matched, anti-alias and high IF filter is depicted in Fig. 4

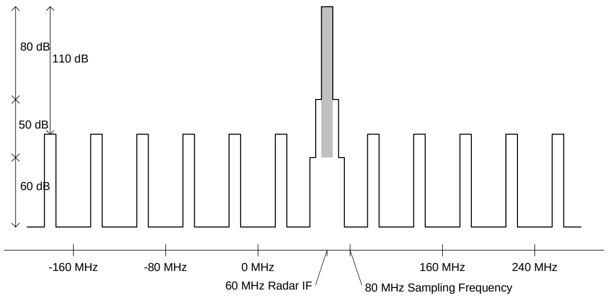

Fig. 6: Combined response of matched, anti-alias and 2^{nd} IF filter

It can be seen that the filter cascade rejects out-of-band signals by at least 110 dB.

Please not that this is a theoretical reflection. Any receiver will always be limited by its noise floor. The filter topology should therefore target at keeping the dynamic range of the receiver free of out-of-band signals.

6 CONCLUSIONS AND FINAL REMARKS

The technical requirements of WLANs operating in C-Band and their impact on radar receivers were explained. Possible mitigation approaches were suggested. A receiver design which is robust against interferences was presented. It is possible to reduce interference from WLANs but because of the RID requirements a complete suppression of interferences may not be possible in all situations. It must also be mentioned that the impact of spurious and out-of-band emissions of WLANs were not considered here.

7 REFERENCES

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