Protection Ratios for FM interfered with by digital broadcasting signals

Compilation of Results of Present Investigations, Thoughts on Protection Ratio Values and on Appropriate Measurement Concepts

1 Initial Position and Motivation for this Report

FM PT45 compiles an initial first draft for a supplement to the ECC report on future possibilities for the digitalisation of Band II 'Technical Elements and Parameters for Digital Terrestrial Broadcasting in Band II'. The candidate digital broadcasting systems for a possible future use in Band II are DRM (Mode E), HD-Radio and RAVIS.

The essential regulatory criterion to meet to deploy a digital broadcasting system in the overcrowded Band II is to fulfil the legal conditions defined in the Final Acts of Geneva 1984 (GE84), which state that, inter alia, '*alternatively, other systems having different characteristics (e.g. other pre-emphasis characteristics, digital modulation) may be used, provided that such use does neither cause greater interference nor demand higher protection than the reference system indicated in the plan*'.

To open this regulatory door for 'digital candidates' it is mandatory to work out if the above mentioned criterion of GE84 can be met by the candidate digital broadcasting systems (FM interfered with by the candidate digital broadcasting systems in their respective different modes, ranging from hybrid to full digital and other derivates).

Therefore, this report aims at

- summarizing the results of present measurements of protection ratios for FM interfered with by DRM and HD-Radio,
- specifying the effects of interferences in FM radios caused by unwanted OFDM signals and discussing the reasons for the differences between results conducted under laboratory conditions and those under real conditions (field trials),
- presenting first thoughts to define a suitable measurement methodology to determine the interferences caused in FM receivers by the candidate digital systems and, based on that, to determine protection ratios for FM which are standardized, consistent, objective and technically fair for all candidate digital systems. The measurement methodology needs, on the one hand, to ensure comparability to ITU-Rec. BS.641 - and therefore, to the requirements of GE84 - and, on the other hand, to take into account the characteristics of state-of-the-art FM receivers, realistic receiving conditions as well as realistic interference situations in the FM adjacent channels (100 kHz spacing).

2 Summary

Measurements of protection ratios for FM interfered with by DRM, and HD-Radio, resp., have recently been conducted by the German Network Agency (BNetzA) together with the University of Applied Sciences of Kaiserslautern (Germany) in 2007 [1] and the National Institute of Telecommunications of Poland in 2006 [3] under laboratory conditions. Furthermore, field trials measurements of protection ratios with DRM as interferer had been conducted in Kaiserslautern (Germany) [2].

Since RAVIS features properties very similar to DRM, the results of the measurements obtained for DRM can be applied mutatis mutandi if the differences (e.g. bandwidth) are considered accordingly.

The results of these measurements (cf. annex, chapter 1) propose that all digital candidates for a future digitalisation of VHF band II

- cannot be deployed taking into account the very critical protection ratio values out of the laboratory measurements which, being based on the measurement method and the specification of the legal ITU recommendations, assume that the FM signal to be protected is interfered with by only one digital interferer (‘one interferer’ situation)
- will have a chance to fulfil the conditions of GE84 taking into account the protection ratio values out of the field measurements which are based on today’s measurement methods and on the real situation (interference limited network and many interferes inside the coverage area), therefore, the new deployed digital system accounts for only one out of many interferers (‘many interferer’ situation)

The interference effects produced by all candidate digital systems mainly depend on the RX characteristics of the FM frontend, e.g., linearity, bandwidth, IF filter characteristics, and FM demodulation process and stem from their Gaussian noise like spectral shape. Since typical FM RX frontends are often non linear (e.g. due to AGC), the interference effects strongly depend on the sum crest factor of the resulting sum interfering signal.

A ‘hybrid TX mode’, i.e. radiating a digital signal in the immediate vicinity of a strong FM signal from the same TX site certainly leads to less interference into FM as compared to a new ‘digital only’, i.e. not co-located TX site. In the latter case, interference into FM may occur especially nearby the ‘digital only’ TX.

A new method to determine suitable protection ratios for FM interfered with by a any digital (OFDM) signal must cover the span between the conditions of GE84, cited in chapter 1, and the need of incorporating the above sketched interference mechanisms. Therefore, the outcomes obtained by such a new method must be interpretable in the light of ITU-Rec. 641 to guarantee -- at least qualitatively -- comparability.

3 Protection Ratios determined until now

3.1 Identifying Interference Effects

In the co-channel, the interference effect is easy to identify: The digital interferer uses the same carrier frequency and, therefore, directly impacts the wanted signal in RX frontend. The interference, and, as a consequence the protection ratio, is about 5 dB higher as compared to an equivalent FM interferer.

In the adjacent channels (± 100 kHz spacing), the proven interference is caused by at least the following effects:

- Gaussian noise like interference in the demodulated composite signal, showing a quadratic increase with AF frequency,
- FM/AM conversion of the Gaussian noise like interference at the IF filter slope,
- Intermodulation caused by the AGC due to the rapid fluctuations of the Gaussian noise like interfering signal producing in-band interference.

These effects are due to the Gaussian noise like nature of the digital signal. Therefore, any interferer having a Gaussian noise like spectral shaping will produce these effects. Now, since the digital systems in question show this Gaussian noise like spectrum (DRM, RAVIS) or have at least respective spectral components (HD-Radio), the above mentioned effects will govern the protection ratios accordingly.

3.2 Lab measurements

The protection ratios for FM interfered with by an OFDM-System as single interferer, i.e. in digital mode only, based on ITU-Rec. 641 'Determination of radio-frequency protection ratios for frequency-modulated sound broadcasting' as compared to the case being interfered with by FM (0 dBr) can be summarized as follows:

- Co-channel and first adjacent channel (± 100 kHz) : +5 dBr ,
- from ±200 kHz to ±400 kHz: Ranging from -5 dBr to +25 dBr,
- Up to ±2 MHz: measurable interference.

In a hybrid mode (hybrid signal made of a strong FM signal and a digital signal in the immediate frequency vicinity), interference higher than allowed by the FM-FM protection ratio curve only occurs in the frequency neighbourhood of the digital signal portion, otherwise, the FM part mainly accounts for interference. This is the case for the HD-Radio hybrid mode in ±200 kHz, where the protection ratio is 18 dB higher as compared to FM-FM. It lies at hand that this result can be applied accordingly for other systems having such a hybrid mode.

3.3 Field Measurements

Within the bandwidth of the digital signal (100 kHz for DRM), interference effects lead to a protection which is about 5 dB higher as compared to FM, fully in line with the lab measurements.

In the adjacent channels, the results out of lab measurements and those out of real field measurements differ significantly: In adjacent channels > ±100 kHz, the protection ratio drops below the value proposed by the ITU curve, and is no longer measurable for offsets greater than ±400 kHz.

At least two effects seem to be responsible for that:

- the background noise limits the RF dynamics (and thus AF quality),
- the received signal is made up of many statistically independent signal components of different power levels (not only one by one signal as in the lab measurements) which reduce the influence of the fast amplitude variations of the DRM signal on AF quality.

3.4 Influence of the Crest Factor

The protection ratio is influenced by the crest factor of the digital signals (cf. annex, chapter 3).

Lab measurements performed in Kaiserslautern for the one interferer case propose that the protection ratio reduces if the crest factor of the interfering signal reduces. This decrease gets smaller the smaller the original crest factor is, however (and obviously), crest factor and protection ratio do not relate in a linear way.

In the multiple interferer case, the protection ratio reduces if the sum crest factor of all signals received is lower than the crest factor observed in an equivalent one interferer situation, which is the case for HD-Radio.

Furthermore, in a given interference situation defined by the sum crest factor of all relevant interfering signals, the audible interference increase will be negligible if an additional interfering digital signal does not significantly increase the sum crest factor. This is the typical real reception situation in an interference limited real environment with many interfering signals. The effect that an additional digital interferer substantially increases interference will not occur nearby the interfered station but in a certain distance from the interfered station, depending on the difference of the power level with and the power level without the additional digital interferer.

4 Thoughts of Protection Ratio Values

Based on the hitherto existing findings, to diametrically opposed protection ratio ranges applicable to the adjacent channels (> ±100 kHz) for the protection of existing FM stations interfered with by digital signals can be identified:

- **Critical range**, defined by the lab measurements, i.e. the ‘one interferer’ situation.
- **Non-critical range**, defined by real receiving conditions in which the digital signal only accounts for a portion of the sum interfering signal, i.e. the ‘multiple interferer‘ situation

As an example for this discrepancy, the following figures can be deduced from lab/field measurements (see annex, chapter 1):

Frequency offset	0 kHz	±100 kHz	±200 kHz	±300 kHz	±400 kHz
Protection ratio for FM					
interfered with by FM; ITU-Rec. BS.412-9	45 dB	33 dB	7 dB	-7 dB	-20 dB
interfered with by DRM in the lab	51 dB	30 dB	-6 dB	-7 dB	-8 dB
interfered with by DRM in the field	51 dB	30 dB	-9 dB	-40 dB	-40 dB

For any digital system, for **coordination purposes**, two sets of protection ratios could be defined:

- **Digital Only:** In this scenario, a new 'digital' TX operates from a new site, i.e. a site where no FM broadcasting in the frequency vicinity takes place from this site. Within its coverage area, the digital TX certainly dominates other (FM) stations in terms of RX field strength level. Consequently, in this mode, not only the usable field strength level but also the expected sum crest factor should be taken into account: The applicable protection ratio, starting from the ±200 kHz adjacent channel, should depend on the increase in sum crest factor.

  An example for such a scenario is a new stand-alone DRM, RAVIS or HD Radio (in full digital mode) site.

- **Digital Hybrid:** In this scenario, the 'digital' TX is co-located with one or more FM TX broadcasting in the frequency vicinity of the digital signal. Within the coverage area of these FM stations, the new digital TX acts as additional interferer. In this mode, an existing FM TX could easily be replaced by a digital TX (100 kHz bandwidth) just by lowering the TX power level by 5 dB. Nevertheless, critical receiving locations (that is, locations where the digital signal is the dominating interferer to the existing FM signals) should be considered carefully.

  An example for such a scenario is a adding a DRM or RAVIS TX to an existing FM site or using the HD-Radio hybrid mode.

In addition, the immense 'bandwidth' of FM receivers (ranging from 'good' to 'bad' for mobile and portable/stationary reception) must be mapped adequately into these two rather opposing protection ratio scenarios.

5 Thoughts on Measurement Concepts

This section presents some thoughts on suitable measurement concept for protection ratios. This is done by first commenting the corresponding ITU recommendation and then discussing the constraints for any suitable approach to re-define the measurement paradigms.

ITU-R BS.641: *Determination of Radio-Frequency Protection Ratios for Frequency-Modulated Sound Broadcasting* describes a procedure for the identification of interference between FM signals. An extension for the determination of interference experienced by digital systems and originating from digital systems is necessary. The FM audio criterion used to determine the protection ratio neither produces audible interference nor reflect today's FM broadcasting reality. It should be modified in such a way that audible interference is evaluated, e.g., based on SINAD (cf. e.g. SINAD's application in narrowband FM radio systems). In addition, this value should be defined for typical FM receivers, e.g. portable devices, automotive devices etc.

ITU-R BS.412-9: *Planning standards for terrestrial FM sound broadcasting at VHF* prescribes a planning procedure which accounts neither for today's FM receiving scenarios nor for today's FM receiver technologies. As a consequence, the predicted TX coverage areas do – by far – not coincidence with those areas where FM reception is actually possible. New and/or modified FM protection ratios (modified ITU-R BS.641) need to be defined, and protection ratios for digital into analogue scenarios and vice versa must be included.

ITU-R BS.704: *Characteristics of FM sound broadcasting reference receivers for planning purposes* defines a reference receiver which is not representative for today's receiver universe. The technical parameters should be revised. In addition, new reference receivers should be defined for different receiving scenarios. Digital reference receivers should be included.

ITU-R SM.1140: *Test procedures for measuring aeronautical receiver characteristics used for determining compatibility between the sound broadcasting service in the band of about 87-108 MHz and the aeronautical services in the band 108-118 MHz* suggests a measuring procedure to assess the interference potential of FM broadcasting services into aeronautical radio services above 108.0 MHz. New protection ratios based on digital systems as interferer must be included.

As a today's matter of fact, the Final Acts of Geneva 1984 are based on the above mentioned recommendations, but state that '*alternatively, other systems having different characteristics (e.g. other pre-emphasis characteristics, digital modulation) may be used, provided that such use does neither cause greater interference nor demand higher protection than the reference system indicated in the plan*'.

Therefore, any measurement concept for the determination of protection ratios for FM interfered with by digital systems in Band II should take these recommendations as starting point to ensure 'backward compatibility' with ITU-R BS.641 (to satisfy GE84), take into account the interference effects discussed above (which, as of today, are not mapped into the measurement method) and introduce technical criterions allowing to objectively rate audible distortion introduced by interfering signals (which, again, is not considered as of today).

In order to work out and to define protection ratios for international (cross border) and national network coordination procedures, a state-of-the-art reference FM receiver should be defined, a receiver, which correctly represents the legal FM-FM protection situation. The difficult point here is that, in the official FM planning and coordination world, nominally only fixed reception is protected; a reception situation which not necessarily reflects 'typical' use of FM radio. This means that new representative RX scenarios (in terms of multi-interferer & multipath) should be identified, evaluated based on the reference receiver and mapped into suitable protection ratios. This could be a good opportunity not only to broaden the measurement concepts, but also to define new additional FM-FM measurement setups to better reflect today's reality (e.g. audio compressed stereo FM interferer with ±75 kHz deviation and 0 dBr modulation power, multi-interferer situation, multipath reception conditions[1]).

Please note that defining a reference receiver does not aim at matching the 'RX universe' but to serve as a valid modern technical basis for network planning and coordination. This implies the reversal conclusion that planning does not guarantee reception for *every* FM RX out of the FM RX universe in *any location* under *any condition* within the 'nominal' coverage area, but the converse is also true: Depending on the RX, reception might be possible even far outside the coverage area[2].

[1] Since FM is an inherently non linear modulation, multipath propagation (linear distortion) leads to non linear distortion in the demodulated AF signal even in the case of an ideal FM receiver/demodulator.

[2] This reflects the situation encountered today in the FM landscape.

Besides defining planning and coordination methods and concepts, an appropriate (national) measurement set up to access both the FM interference and the FM coverage situation at a test location should be elaborated. Again, these procedures should inter alia rate the perceived audio quality (as it should be the case for protection ratio measurement) and not purely rely on RF signal levels (as it is today). The measurement setup should allow verifying the planned coverage, the interference situation as well as the perceived audio quality. The audio quality should be the ultima ratio to determine whether or not a location is considered to be 'interfered' or not. Ideally, such a setup is based in the reference receiver.

Kaiserslautern, Ludwigshafen; 6th December 2010

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ANNEX

1 Measurements of Protection Ratios for FM interfered with by DRM

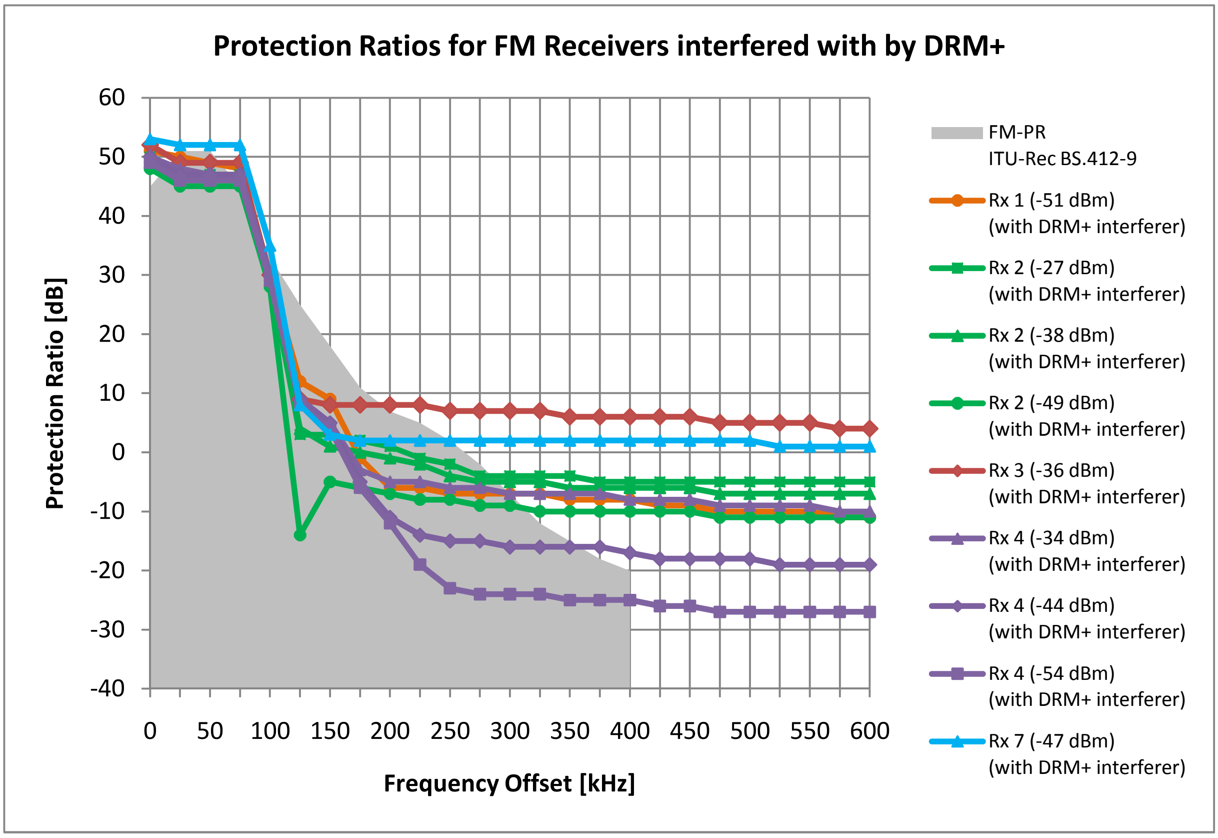
Measurements of protection ratios for FM interfered with by DRM and HD-Radio, resp., had been conducted at the University of Applied Sciences of Kaiserslautern (Germany) together with the German Network Agency (BNetzA) in 2007 [1]. The measurement of protection ratios had been conducted according to the respective ITU recommendations. A total of 7 analogue FM broadcast receivers were available. Due to the limited amount of time, not all receivers were tested for all interference signals. Protection ratio measurements with FM broadcast as the interferer have shown, however, that RX 1 (JVC CA-MX55RMB Hifi Rack) has a representative behaviour against FM interfering signals as compared to the relevant curve published in ITU-R BS.412-9 (cf. Figure 2) and other receivers tested.

In a field trial, also conducted by the University of Applied Sciences of Kaiserslautern (Germany) in 2008, protection ratio for FM had been determined in realistic frequency and interferences environments [2]. Again RX 1 was used as reference receiver.

1.1 Results of Lab Measurements

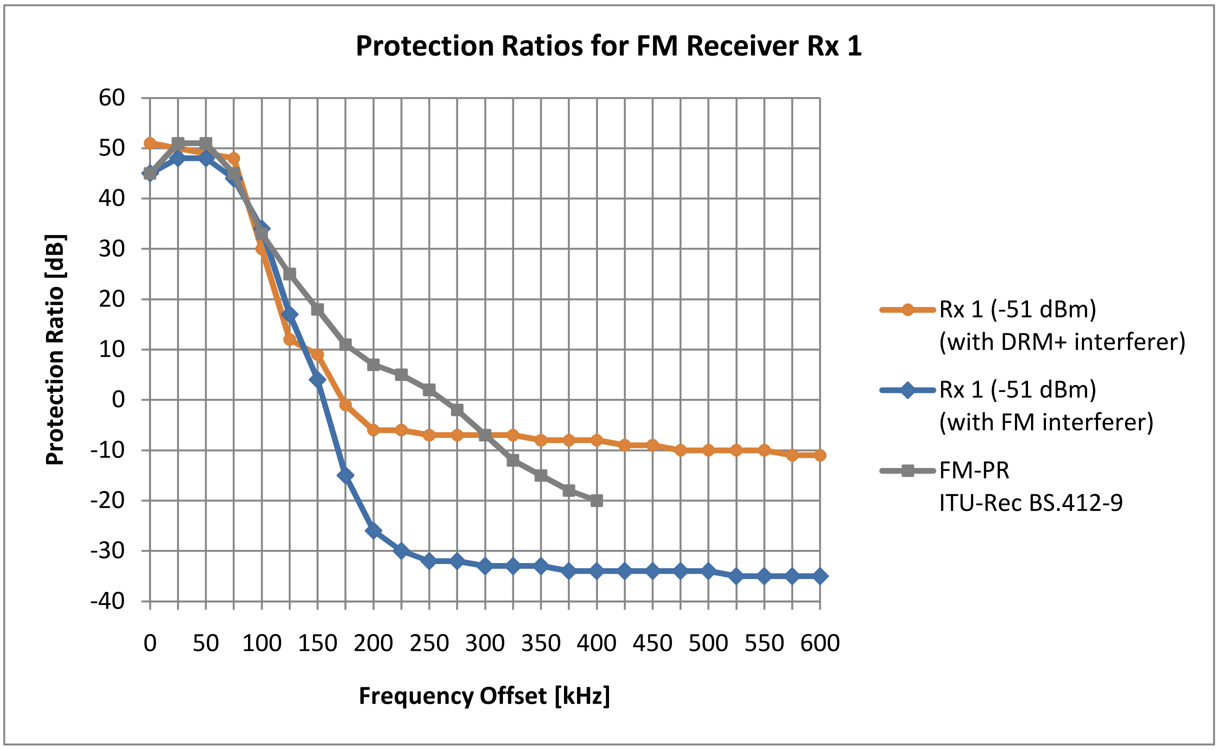
The protection ratios for FM interfered with by DRM using different RXs are given in Figure 1.

Figure 1



The protection ratios for FM broadcast interfered with by DRM and by FM, resp., using RX 1, are given in Figure 2.

Figure 2



The protection ratios for FM out of these measurements are given in Table 1.

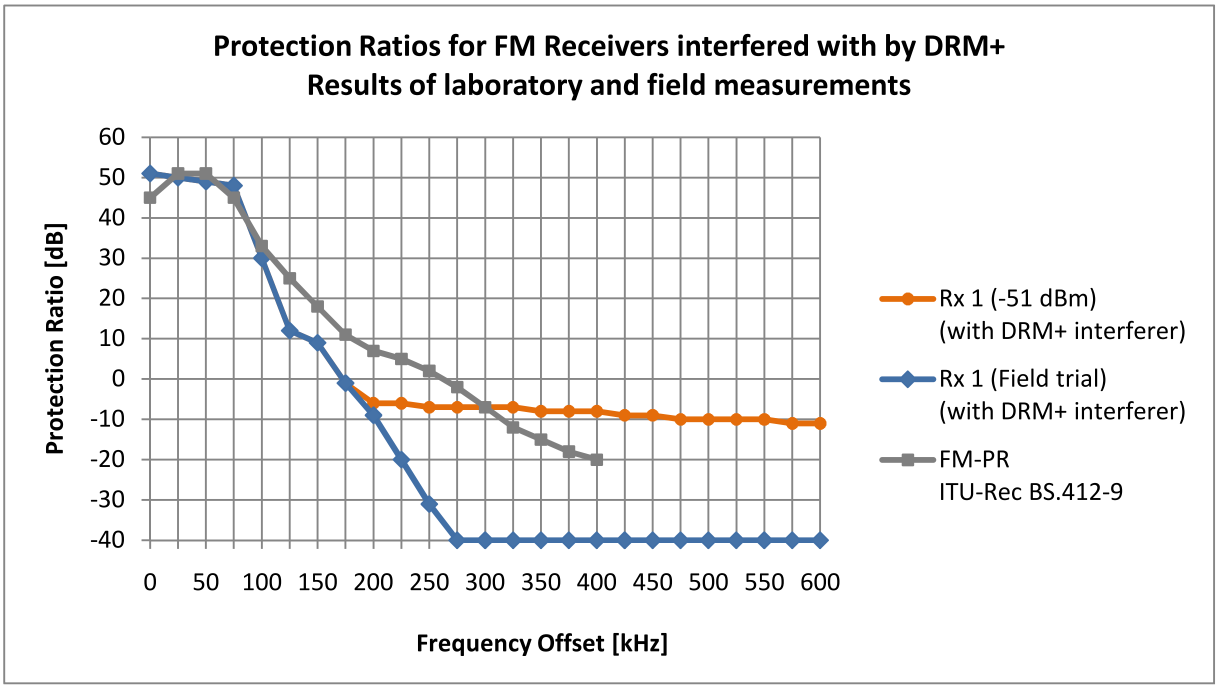
Table 1

Frequency offset	0 kHz	±100 kHz	±200 kHz	±300 kHz	±400 kHz
Protection ratios for FM interfered with by FM (ITU-Rec. BS.412-9)	45 dB	33 dB	7 dB	-7 dB	-20 dB
Protection ratios for FM interfered with by FM for RX 1	45 dB	34 dB	-26 dB	-33 dB	-34 dB
Protection ratios for FM interfered with by DRM for RX 1	51 dB	30 dB	-6 dB	-7 dB	-8 dB

1.2 Results of Measurements in Field Trial

The protection ratios for FM broadcast interfered with by DRM that have been determined with RX 1 in the field trial 2008 [2] are given in Figure 3. To compare to the results out of the laboratory measurements the respective protection ratios are also given.

Figure 3



1.3 Conclusion

Based on the present findings on compatibility of DRM into FM the following conclusion seems to be obvious:

As compared to the outcomes of the laboratory measurements, compatibility of DRM into FM is much easier to achieve in real world reception conditions. This phenomena arises from the fact that

- the background noise limits the RF dynamics (and thus AF quality),
- the received signal is made up of many statistically independent signal components of different power levels (not only two, i.e. the 'wanted' and the 'interferer') which help to reduce the influence of the fast amplitude variations of the DRM signal on quality.
- DRM signals feature a higher crest factor than FM signals (6 … 12 dB as compared to 0 dB), leading to a higher intermodulation potential in typical FM receivers, resulting in a higher degradation of perceived AF quality. This means that a DRM signal has an inherently higher absolute interference potential as compared to FM as long as it not filtered out before the first mixer stage.
- The pshophometrically weighted (S/N) of 50 dB, which is the basis for the planning standards for FM sound broadcasting networks, is merely achieved in real world reception conditions, irrespective of whether the receiver has this sensitivity or not. This is due to the inevitable background noise (i.e. co-channel interference) as already stated before.

- Provided proper bandpass filtering at the TX output the field trial outcomes propose that – as compared to FM to achieve compatibility – for the DRM power needs to be lowered by about 5 dB
- In the vicinity of a DRM TX, where the DRM signal typically dominates the received signal, the interference potential of DRM is generally higher as compared to FM.

The protection ratios for FM interfered with by DRM out of the lab and field measurements are given in Table 2. The values in the co-channel and in the first adjacent channel are identical, but there is a high mismatch in the adjacent channels starting from ±200 kHz on.

Table 2

Frequency offset	0 kHz	±100 kHz	±200 kHz	±300 kHz	±400 kHz
Protection ratios for FM interfered with by FM (ITU-Rec. BS.412-9)	45 dB	33 dB	7 dB	-7 dB	-20 dB
Protection ratio for FM interfered with by DRM in the lab environment	51 dB	30 dB	-6 dB	-7 dB	-8 dB
Protection ratio for FM interfered with by DRM in the field environment	51 dB	30 dB	-9 dB	-40 dB	-40 dB

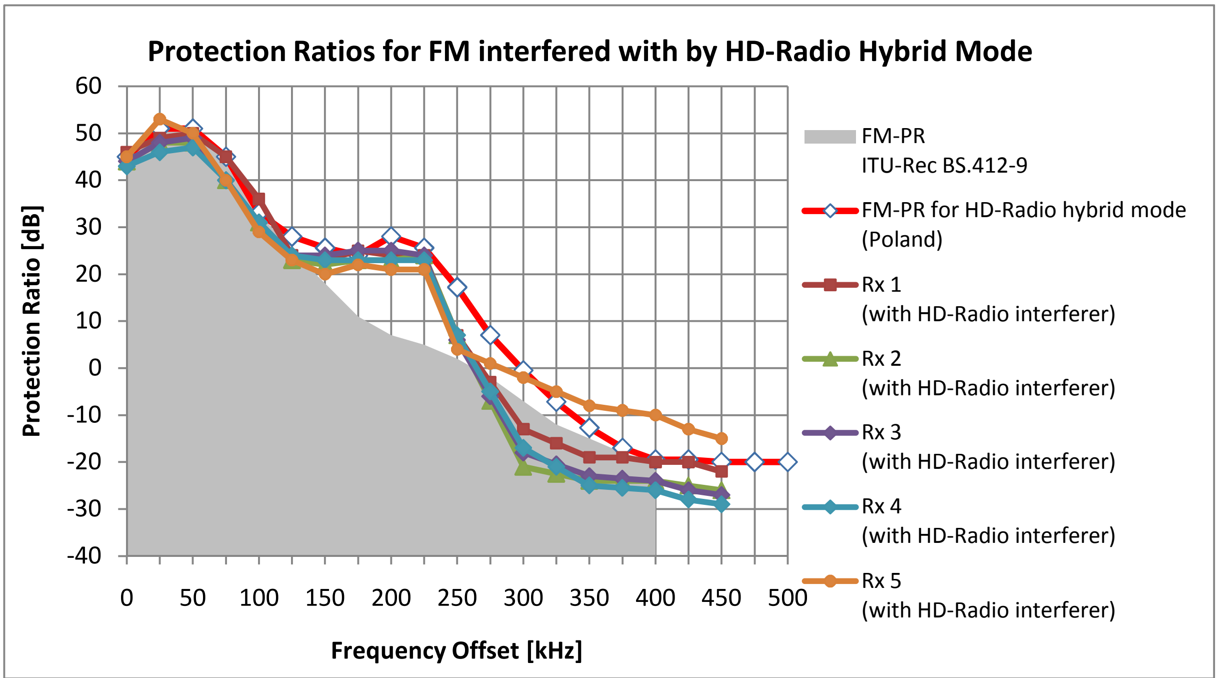
2 Measurements of Protection Ratios for FM interfered with by HD-Radio

Measurements of protection ratios for FM interfered with by HD-Radio both in hybrid mode and in digital mode, resp., had been conducted at the National Institute of Telecommunications of Poland [3] in 2006 and by HD-Radio in hybrid mode at the University of Applied Sciences of Kaiserslautern (Germany) in 2007 [1].

2.1 Results of Lab Measurements with HD-Radio Hybrid Mode

The protection ratios for FM stereo interfered with by HD-Radio out of the measurement of the National Institute of Telecommunications in Poland in 2006 [2] with HD-Radio hybrid mode and for different RX (RX 1 – RX 5) out of the lab measurements in Kaiserslautern in 2007 [1] are shown in Figure 4.

Figure 4



For offsets up to ±150 kHz the interfering effect of HD-Radio is nearly equal to an FM broadcast interference. Especially for offsets between ±150 kHz and ±250 kHz, however, the required protection ratio is up to 20 dB higher compared to an FM broadcast interferer. Keeping in mind that the average protection ratio of the measured receivers against FM broadcast interferers was much less than specified in ITU-R BS.412, the interference potential of HD-Radio is higher for all offsets between ±100 kHz and ±300 kHz.

The protection ratios for FM out of these measurements are given in Table 3.

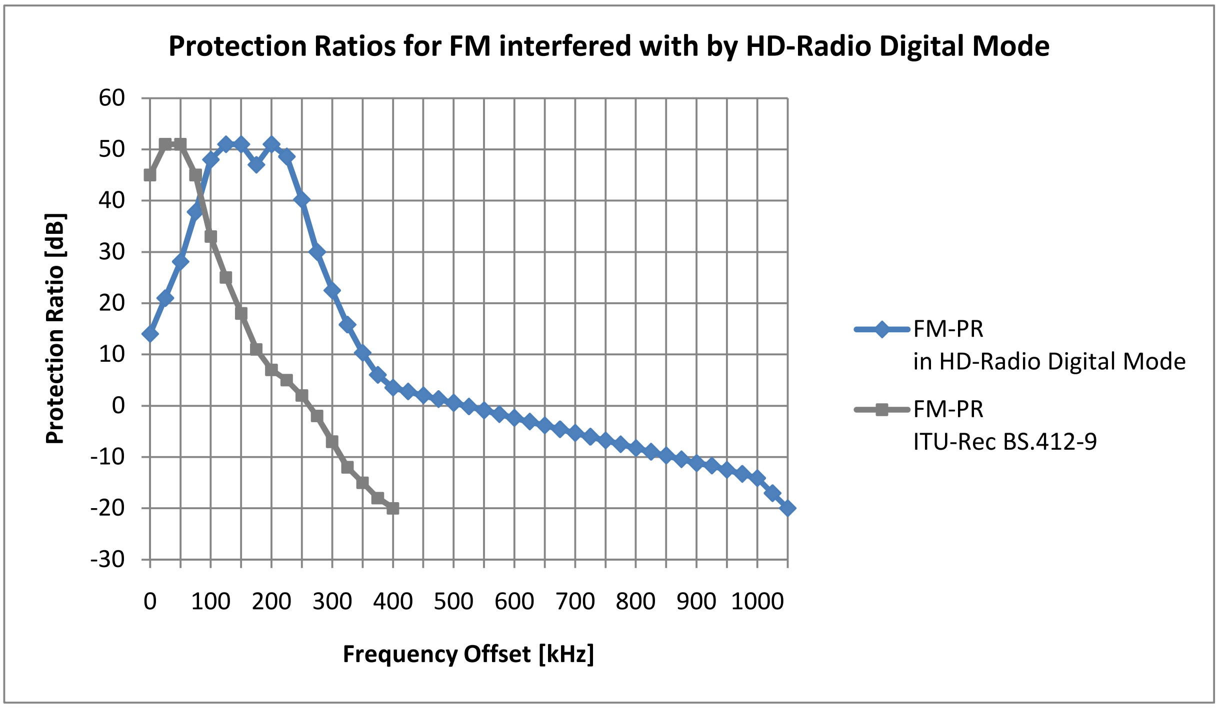
Table 3

Frequency offset	0 kHz	±100 kHz	±200 kHz	±300 kHz	±400 kHz
Protection ratios for FM interfered with by FM (ITU-Rec. BS.412-9)	45 dB	33 dB	7 dB	-7 dB	-20 dB
Protection ratios for FM interfered with by HD-Radio hybrid mode	45 dB	33 dB	25 dB	-7 dB	-20 dB

2.2 Results of Lab Measurements with HD-Radio Digital Mode

The National Institute of Telecommunications in Poland conducted not only measurements with HD-Radio hybrid mode but also with HD-Radio digital mode in modes MP5 – MP7 in 2006 [2]. The determined protection ratio curve is given in Figure 5.

Figure 5



Due to the lack of a carrier in the centre of the HD-Radio signal the interferences impact in the FM co-cannel is low. But in the adjacent channels from ±100 kHz on the disturbance is significant. For the offsets greater than 400 kHz, the proposed protection ratio reaches a value of −20 dB only for ± 1.1 MHz offsets. Its value is approximate and, even though it is highly probable, requires further measurements and research. It is impossible to evaluate the possibility of introducing full digital HD Radio system [2].

The assumed values for the protection ratios for FM out of these measurements are given in Table 4.

Table 4

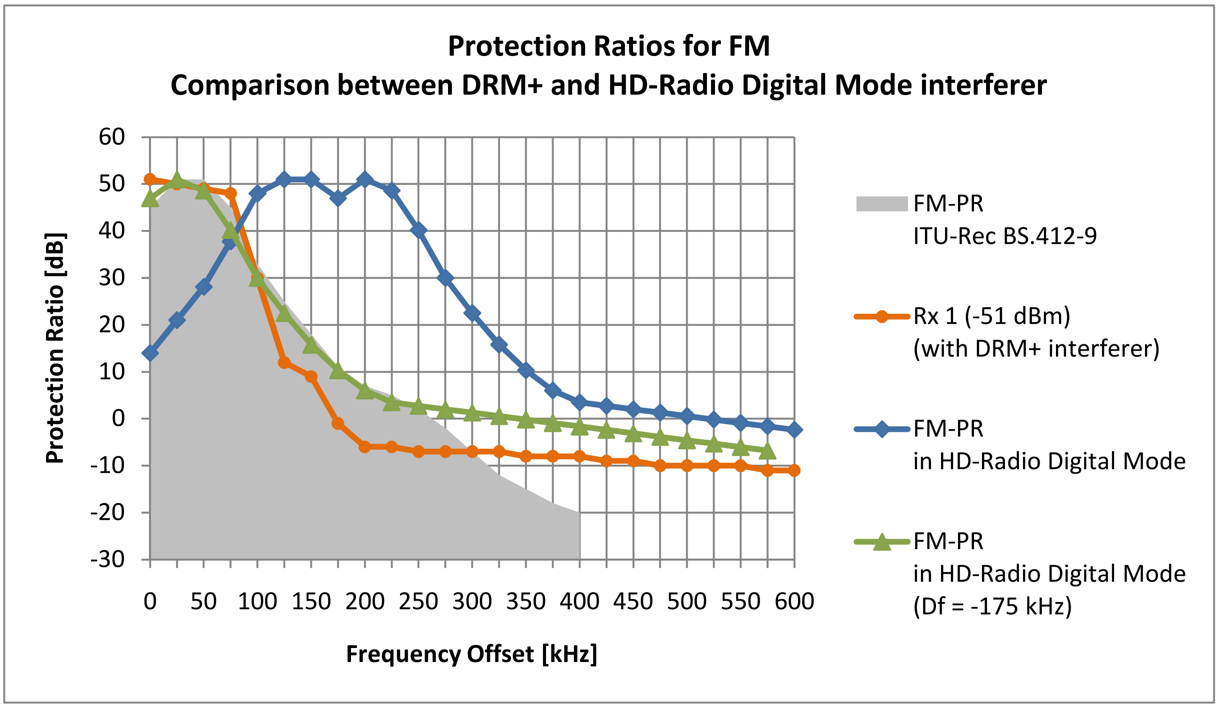
Frequency offset	0 kHz	±100 kHz	±200 kHz	±300 kHz	±400 kHz
Protection ratios for FM interfered with by FM (ITU-Rec. BS.412-9)	45 dB	33 dB	7 dB	-7 dB	-20 dB
Protection ratio for FM interfered with by HD-Radio digital mode	14 dB	48 dB	51 dB	22 dB	4 dB

2.3 Comparison between DRM and HD-Radio Digital Mode

The protection ratios for FM interfered with by DRM and by HD-Radio digital mode, resp., are given in Figure 6.

To make the interferences impacts of DRM and HD-Radio digital mode on FM comparable, the curve of HD-Radio had been moved by -175 kHz (green curve). It is obvious that HD-Radio shows the same impact as DRM when the HD-Radio digital mode is used.

Figure 6

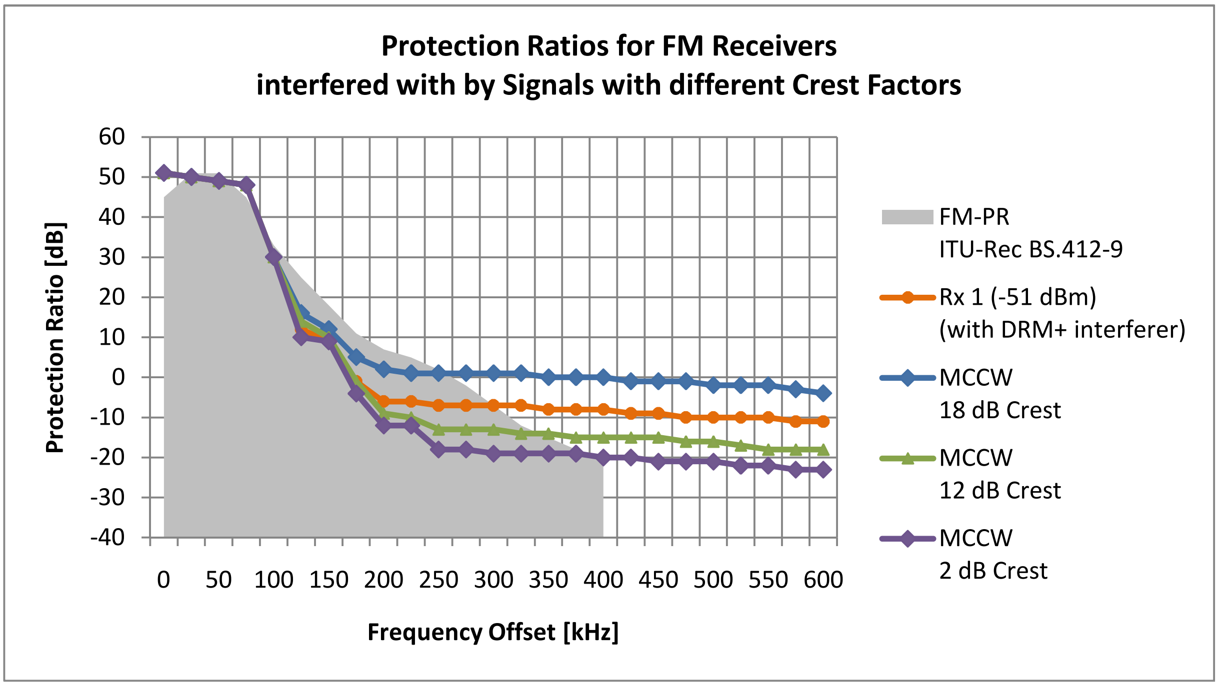


It has to be mentioned that, in contrast to DRM, HD-Radio has *two* OFDM blocks and therefore *two* frequency ranges with high interference which is *not* shown in the figure. The main interference range then goes from -400 kHz to +400 kHz and is quite different from the impact of HD-Radio in hybrid mode.

3 Impact of the Crest Factor

The impacts of OFDM interferers in the FM adjacent channels can be improved by decrease of the crest factor of the interference digital systems. The University op Applied Sciences conducted additional measurements with digital interference signals that have different crest factors. The results are given in Figure 7. As it is shown the protection ratios in the adjacent channels decrease when a low crest factor is given.

Figure 7



As it is shown in annex, chapter 2, HD-Radio in hybrid mode has a negligible impact in the adjacent channels. The reason is that the FM signal, which has 20 dB more power that the HD-Radio signals, reduces the total sum crest factor of the HD-Radio in digital mode from 9 dB to 2 dB.

On the other hand even though an ideal FM modulated signal has a crest factor of 0 dB, the superposition of uncorrelated FM signals effects a higher crest factor as 0 dB.

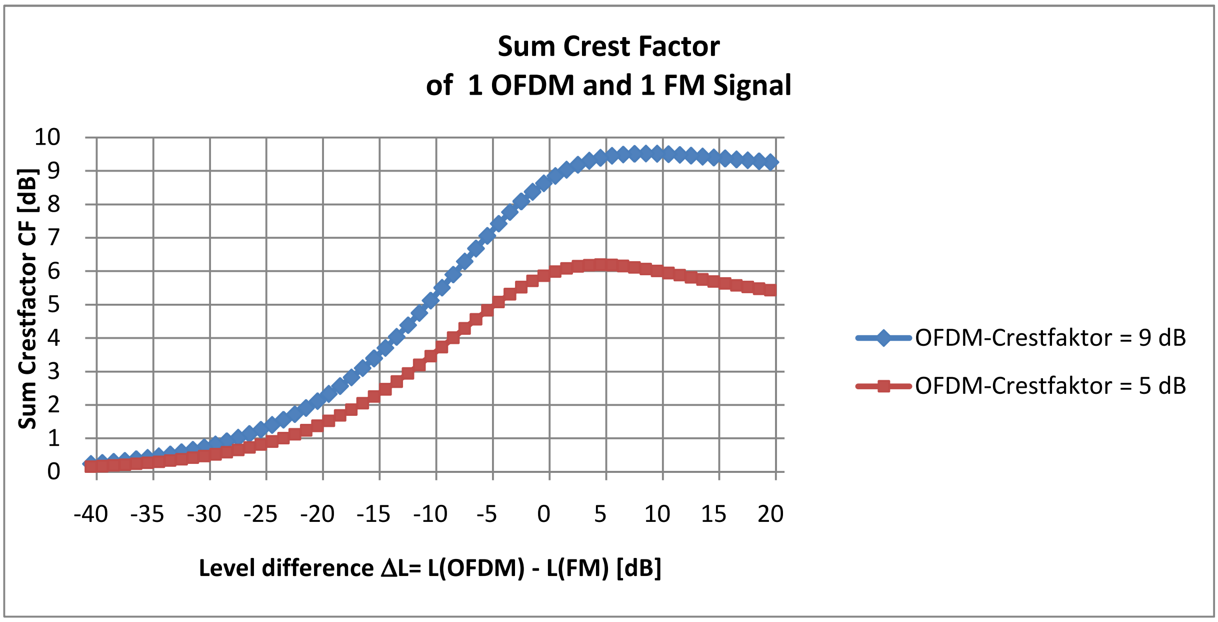
Generally the sum crest factor of different statistically independent signals can be calculated by the formula

$$CF = 20\log_{10}\left(\sum_{k=0}^{n} 10^{\frac{E_k+CF_k}{20\,dB}}\right) - 10\log_{10}\left(\sum_{k=0}^{n} 10^{\frac{E_k}{10\,dB}}\right)\ [\mathrm{dB}]$$

where E_k is the field strength of the k-th signal [dBμV/m] and CF_k is the crest factor of the k-th signal [dB].

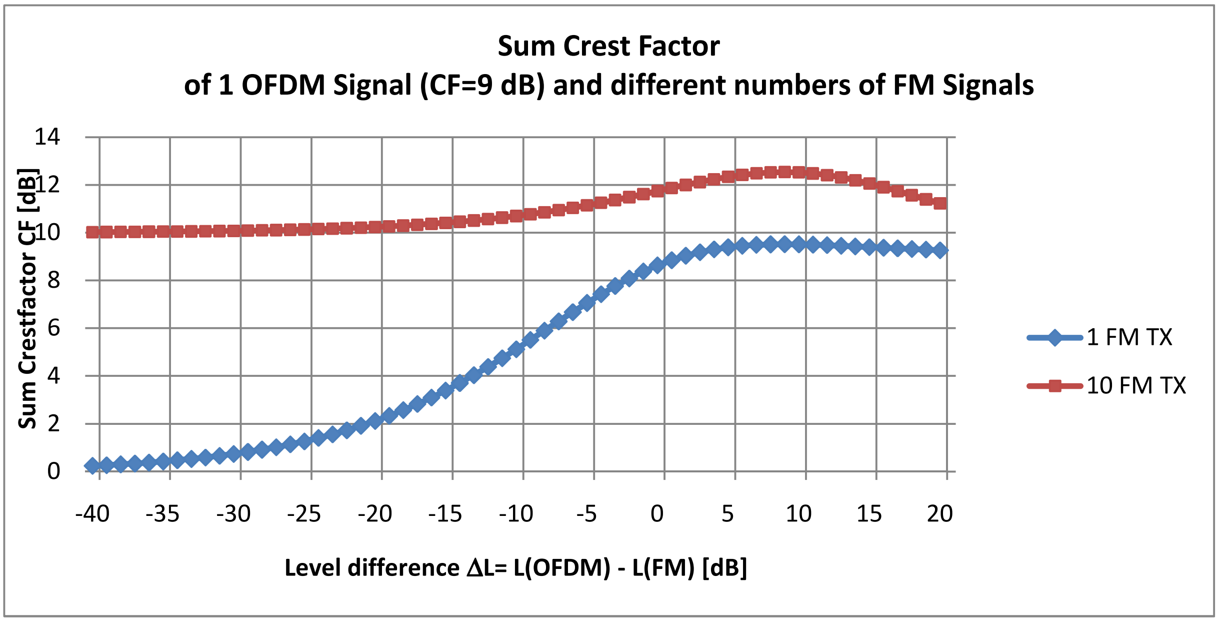
As an example the sum crest factor of one FM signal and one signal with a crest factor of 5 dB and 9 dB, resp., is given in Figure 8. As can be seen, a sum crest factor of 2 dB is obtained for a power level difference of -20 dB, which corresponds to the crest factor of HD-Radio in the hybrid mode.

Figure 8



As another example the values of the sum crest factor, taking into account 10 FM signals with identical power and an additional signal with variable crest factor has been calculated. The result is shown in Figure 9. Even in the case that an additional signal has a high crest factor (here 9 dB) the increase of the sum crest factor is 2.2 dB at maximum. It has to be noted that the maximum rise of the sum crest factor doesn't lie in the vicinity of the transmitter site of the additional (OFDM) signal (power level difference > 20 dB) as expected but in the range of the power level difference of about 5 to 15 dB.

Figure 9



4 References

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