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Intended signals and ambient electromagnetic noise in HF spectrum management

Ben A. Witvliet(1,2), Erik van Maanen(1), Rowan de Vries(1), and Laurens Bakker(1)
(1) Ministry of Economic Affairs & Climate, Dutch Authority for Digital Infrastructure, Groningen, The Netherlands.
(2) University of Twente, Faculty of EEMCS, Radio Systems group, Enschede, The Netherlands,
e-mail b.a.witvliet@utwente.nl.

Abstract

Both spectrum management – the organization of radio services in the spectrum to maximize spectrum utility – and radio link planning and the associated equipment design require a-priory knowledge of the electromagnetic environment. The dynamic range of the planned radio system must be able to support the accumulated power of intended radio signals within the bandwidth of the receiver front-end, and the ambient electromagnetic noise field strength must be accounted for in the link budget calculations. These items are especially important for sensitive receivers in the HF (3-30 MHz) frequency range, e.g. for radio astronomy or emergency communications. This paper will discuss these spectrum management and equipment design issues, with an emphasis on ambient electromagnetic noise.

1. Introduction

Since the introduction of the first wireless communication services by Marconi's Wireless Telegraph Company in 1907 [1], our society has become more and more reliant on wireless technology. In the early years, the receivers of these radio systems were hardly frequency-selective, and the spark-gap transmitters emitted a wideband noise-like signal with many harmonics. The number of transmitters was limited. Consequently, the first international radio planning conference in 1906 [2] mainly discussed operational issues, such as interoperability and the standardization of distress signals, and it did not touch frequency planning. However, the number of transmitters and receivers worldwide has increased from a few hundred in the 1920's, to several billion [3] in 2020, and as a result, the electro-magnetic spectrum has become crowded. Fortunately, technology has advanced, and the transmitters and receivers are now frequency-selective and stable, the transmitted signals well-defined and bandwidth limited, and the transmission protocols efficient and adaptive. Therefore, these days, the World Radiocommunication Conferences [4] deal with frequency allotments and medium sharing protocols, to provide each application with a slice of the pie. The attributed spectrum can be defined in portions of frequency spectrum, time slices or geographical areas, or a combination of all three [5].

The bases of these frequency sharing solutions is the 'coexistence study', a calculation of the probability to the wanted wireless system in the presence of other electromagnetic signals on the same frequency or elsewhere in the spectrum. For the coexistence studies, Monte-Carlo simulations or other statistical methods are used to find optimal parameters for efficient and effective sharing of the spectrum [6]. The link budget calculations used in these simulations are similar to the calculations that would be made by a research laboratory designing an individual system for a specified robustness in an expected radio frequency (RF) environment. The 'other signals' in these studies can be intentional transmissions from other spectrum users. But they can also be unwanted by-products of intentional transmitters or noise-like unwanted emissions from other electrical and electronic devices, or even noise from natural sources.

The impact and impact mechanisms of intentional signals are discussed in Section 2. In Section 3 we discuss the impact of an increased ambient electromagnetic noise level. Section 4 discusses the importance of the work on radio noise measurements and models in Study Group 3 of the International Telecommunication Union (ITU). A conclusion is presented in Section 5.

2. Impact mechanisms of intentional signals

The designs of an individual radio system, whether that is a high-end radio astronomy receiver or a consumer-grade remote control system, requires information about the expected RF environment. That environment consists of a large number of intended transmitters and the background ambient noise level. In this Section, we'll discuss the possible impact of the intended transmitters and the associated impact mechanisms.

When the receiver receives both the wanted transmitter and another transmitter, interference may – but need not – occur. Whether interference occurs depends for a large part on the ability of the demodulator of the receiver to discriminate between the wanted modulation and coding and other signals. The required minimum ratio of the wanted field strength over the field strength of other transmitters is called the 'Protection Ratio' (PR). Both the demodulator and the analog or digital filtering prior to it provide additional discrimination of unwanted transmitters that have a frequency offset with the wanted transmitter, and therefore PR is offset dependent:

$$\frac{Field\ strength\ (wanted)}{Field\ strength\ (other)} \geq PR(offset) \tag{1}$$

Figure 1 shows a measure curve for Terrestrial Digital Video Broadcasting (DVB-T2) reception, taken from [7, Table 24]. In this case, the interferer is also a DVB-T signal. The values will be different for an interferer that has a different spectral shape and texture.

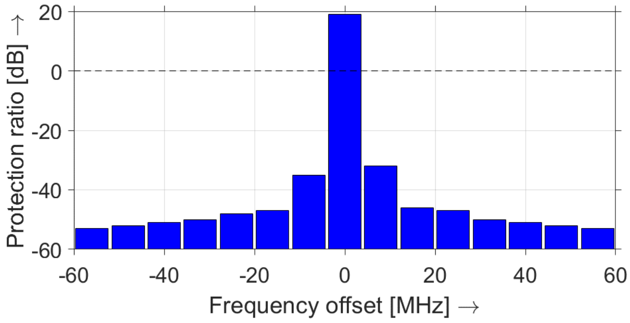

Figure 1. Example of measured PR curve of 11 DVB-T2 receivers [7].

While Figure 1 suggests that transmitters at frequencies that are offset by 40 MHz may be 51 dB stronger than the wanted signal, this is does not provide the complete picture. When analog stages of the receiver prior to the filtering are overloaded by the unwanted signal, their gain lowers significantly and the receiver becomes 'deaf'. This gain reduction by signals on other frequencies is called 'desensitization', or in its extreme form 'blocking'. The same effect may be caused by saturation of the analog-to-digital convertor (ADC) when the channel filtering is done in the digital domain. The saturation level is not a relative level, but an absolute one. Figure 2 shows an example. Blocking and desensitization occurs especially when the interferer is at close range, and therefore the field strength is high.

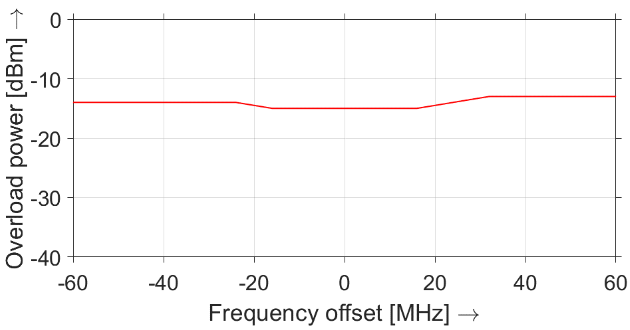

Figure 2. Example of measured overload power of 11 DVB-T2 receivers [7].

But even at lower signal levels, when desensitization does not yet occur, intermodulation in the receiver of two strong signals at frequencies far away from the wanted signal frequency may make a ghost signal appear on the receive frequency and cause interference. This happens when an active antenna or the analog stages in the receiver up to and including the ADC have insufficient linearity. The amount of intermodulation resistance is quantified as the 2nd order and 3rd order Input Intercept Point (IIP2 and IIP3). Second order intermodulation distortion (IMD) products occur at the sum and difference of the input frequencies. Third order products occur at twice the first frequency minus the other. The impact of the latter is shown in Figure 3.

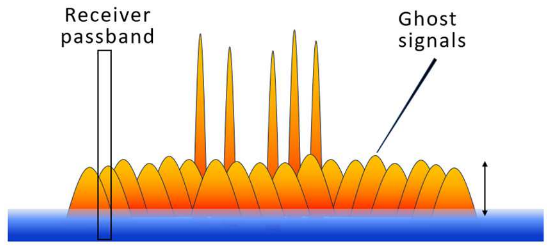

Figure 3. Third order intermodulation products: ghost signals generated in the receiver.

Intermodulation effects are especially important in the HF frequency range, where many very strong signals of broadcast stations are received by ionospheric refraction. In Figure 4, a 24-hour spectrogram of the HF frequency range shows that strongest signals that the receiver has to handle are from the HF broadcast stations. It also shows their relationship with ionospheric radio wave propagation. Data from 15 December 2023 [8].

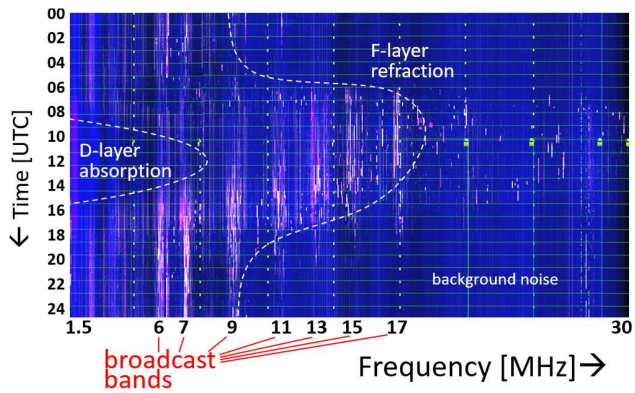

Figure 4. An HF receiver has to remain linear in the presence of many strong broadcast signals.

As we see from the above, receiver parameters play an important role in interference scenarios and spectrum management [9]. One could say that 'interference is in the eye of the beholder'. Inferior receiver quality (demodulator quality, passband filtering, linearity and dynamic range) will cause interference that would not present itself if superior receiver characteristics would have been realized. Interference that cannot be resolved at the side of the (unwanted) transmitter. This unnecessary interference will impede efficient use of the spectrum.

For HF humanitarian communications, receiver linearity is of utmost importance, as their counterparts use low power transmitters. While their highly selective receivers (3 kHz) reject strong signals outside the receive channel, IMD could still generate on-channel ghost signals, masking weak signals. HF radio astronomy receivers generally have large bandwidth, of typically 200 kHz to several MHz. They use advanced algorithms to remove narrowband radio signals, either in the frequency domain, or by determining their direction and removing them from the astronomical image. Here lack of linearity would produce a large number of ghost signals. The ghost signals themselves, being a product of multiple transmitters with varying relative phases, cannot be removed by spatial filtering. Removing their original signals that cause these IMD products will also remove the IMD products, but their detection in a sea of IMD-products is difficult.

3. The impact of ambient background electromagnetic noise on reception

As mentioned before, the ‘other signals’ can also be unwanted by-products from other intentional transmitters or from other electric and electronic devices (not intended as emitters). The other signals can even originate in natural sources, such as lightning, the sun, Jupiter, and the Milky Way, as explained in [10]. When by-products from a large number of unrelated sources of similar strength accumulate, the individual spectra of each source can no longer be distinguished, and a wideband electromagnetic field results, with characteristics that resemble noise. This is even more prominent at HF, where noise from large cities may arrive via ionospheric reflection [11]. An example of this is shown in Figure 3. In (a) the spectral byproducts (harmonics) of a single switch-mode power supply can be seen, while (b) shows the byproducts of a large number of electronic devices, together producing a wideband noise-like spectrum. In the early days of radio, this ambient electromagnetic ‘smog’ has been labelled ‘radio noise’: the noise that you hear in radio equipment as soon as you connect the antenna.

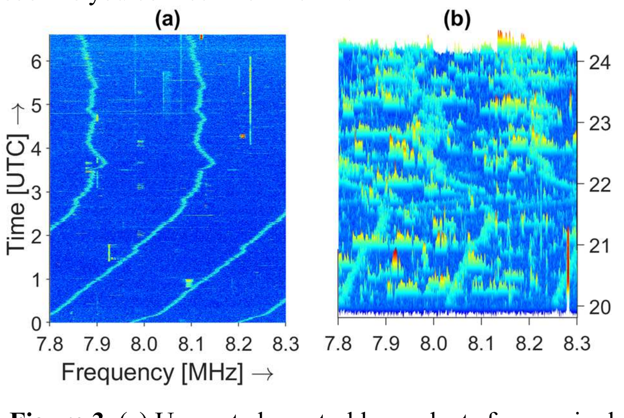

Figure 3. (a) Unwanted spectral byproducts from a single electronic device, (b) accumulated noise from many devices.

When the spectrum of the electromagnetic noise overlaps the receive channel, the signal-to-noise ratio drops and the throughput and reliability of the radio link will deteriorate. If the noise level becomes too high, e.g. when the noise sources are close, reception will be inhibited completely. Even if the noise spectrum does not overlap the receive channel, the total power of the signal outside the passband will contribute to overloading of the input stages of the receiver. Possible mitigation depends on the nature of the noise, whether it is cumulative noise from a large number of unknown sources, or noise from a single or a limited number of identifiable sources. Actions to eliminate the effect of individual sources are usually simpler than for cumulative noise. The former can often be geolocated and subsequently identified by switching off their power source. If they are outside our control, they can still be eliminated from the received signal by determining their spatial direction-of-arrival and applying a spatial filter [12]. This usually solves both the co-channel and out-of-channel effects. However, we should not forget that these methods require antenna arrays and real-time signal processing, which may not be feasible for low cost consumer equipment.

For cumulative noise these actions are more difficult, since there is not a single source that can be eliminated. The noise arrives from a large range of angles and is usually spectrally wideband. Out-of-channel effects can often be countered with improved filtering in the receiver, but co-channel effects cannot be eliminated that way. Diversity reception or beamforming may be used to reduce radio noise, again with the implication of implementation cost. But other than that the only solution to the reduced link budget caused by the ambient electromagnetic noise is an increase in transmitter power or antenna gain. And with that, an increased radio noise level directly affects efficient use of the spectrum and reduces the usable spectral space that is shared by all applications.

4. The importance of ITU radio noise measurements and models

For radio link planning and design, knowledge of the expected radio noise level is essential, as – at least up to 20 MHz – it limits the receiver sensitivity. Also for compatibility studies this knowledge is essential. For example, if the field strength of an unwanted transmitter in protected spectrum is much lower than the expected radio noise, one could argue that its contribution to system performance may be ignored. For these purposes, the ITU provides information on the expected noise level and its nature in Recommendation P.372 [13], for different frequencies and with a differentiation by environment. This standard work on radio noise was created in 1954 and is regularly updated. The latest version is from 2022. Especially the predicted radio noise level in ‘Quiet Rural’ areas is important, as it provides a baseline value, representing the noise level that exists when no local noise sources are nearby.

The radio noise models and graphs in P.372 are partly derived theoretically and verified by measurement (for the frequencies above 300 MHz), and partly entirely empirical (for the lower frequencies). However, establishing trustworthy reference levels for all frequencies, all environments, and then for all countries of the world, is challenging at best. While many radio noise many measurements have been stored in the ITU Radio Noise Data Bank, the measurement data is still far to sparse to give conclusive evidence to define the current graphs. Therefore, Study Group 3 of the ITU is now investigating how the work of Fockens [14] on the relation between the density of electronic devices and their distance to the receiver can be adapted in a modified form for P.372, by adding the radio wave propagation at the observation frequency [10] and the expected wall attenuation (where applicable). The available measurement data may then be used to validate the theoretical models.

Better models will help to provide better feedback to the organizations that establish and update limits in equipment norms controlling unwanted emissions. As Fockens showed, the noise levels increases with the steadily increasing equipment density. This may require the emission level per device to be lowered to maintain an acceptable noise level.

5. Conclusions

On-channel and out-of-channel transmitters may, but need not, cause interference. A more robust receiver – with better demodulator quality, passband filtering, linearity and dynamic range – will be more resilient to interference from out-of-channel signals.

Radio noise also deteriorates the link budget of radio systems. Noise from individual sources can sometimes be eliminated at the receiver, but not without a significant investment in hardware and signal processing. Cumulative noise cannot be eliminated. An increase of the cumulative noise will result in additional cost to the victim and a decrease of available spectrum for all users.

For optimal spectrum management and for optimal system design, an accurate model of the expected radio noise is essential. For this, it is advisable to involve Study Group 3 of the ITU, so that the models become available to all spectrum users, and will be used in international spectrum planning conferences. Noise models need to be validated periodically, so that the actual noise levels and – very important – their trends can be published. For this, empirical data is essential.

6. Acknowledgements

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