Simulation of the Effects of the Residual Low Level PIM to Improve Payload Design of Communication Satellites

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Abstract— The Passive Intermodulation (PIM) is a well known inconvenience in satellite links. It consists in an unwanted generation of harmonics and resulting intermodulation products in weak nonlinear components crossed by RF currents or in irradiation of these unwanted signals by external materials exposed to a strong RF electromagnetic field. Several studies have been carried out to reduce this negative effect and particular measurement techniques have been employed in pre-launch testing of the whole components of the required payload. The extension of the satellite links to mobile communications, which require more transmitted power and increased receiver sensitivity, renders more and more important the reduction of the PIM effects on the downlinks to obtain a satisfactory level of Quality of Service (QoS). This paper reports the simulation results of effects of the third order PIM products in a multichannel transmitting system. The simulations are carried out by using Time-Frequency Representations of the unwanted combinations of spurious signals generated by third order PIM products. The results of the above simulations are interpreted and a first attempt of design guidelines is given.

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1. INTRODUCTION

SOME of the past satellite programs encountered difficulties with passive intermodulation (PIM). This phenomenon generates unwanted effects particularly in the final components of the satellite transmitter, i.e. adduction cables and related junctions, waveguides and antennas. It consists in an unwanted generation of harmonics and resulting intermodulation products in weak nonlinear components crossed by intense RF currents or in a irradiation of these unwanted signals by external ferromagnetic materials exposed to a strong RF electromagnetic field. A detailed description of some satellite programs which suffered this inconvenience is given in [1]. The experience gained by the designers in this field have greatly reduced this parasitic effect in more recent realizations. Anymore, it is still present and represents the object of several studies reported in the recent literature, regarding the behavior of the final elements of the satellite transmitter [2–12]. Moreover, it should be noted that some of the final elements of the transmitter, such as the antenna and related cables and waveguides, are mobile. In the launch phase they are packed into the satellite container and assume the final size and position when the satellite reaches the wanted orbit. The antenna and its related components remain mobile also in the normal service of the satellite. This fact can create new contributes to the PIM. So, a certain relatively low presence of PIM should be taken into account in the design of the whole transmitter. At present, also the entire communication system planning should take into account this effect [13–16], because it increases with the age of the satellite.

Modern design of the transmitter antenna realization takes into account the minimization of the PIM generation [17]. Also the realization technology of the components of the satellite transmitter includes measurements of the unwanted modes performed in an anechoic chamber [2, 18] in order to control and reduce, on basis of the acquired information, the PIM level. All these useful actions are focused on the reduction of the amplitude of the unwanted frequencies, whereas their complete elimination is not a reachable task. So it is very interesting a detailed understanding of the effect of this spurious frequencies over a communication system. A first remark regards the fact that a modern communication system, namely a global system for mobile communications (GSM), is based on the phase variations of a signal. The above described efforts in reducing the PIM effects are focused on the reduction of the amplitude of the unwanted frequencies, because the detailed interaction between the wanted and the unwanted frequencies, in terms of phase interrelations, is very

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complicate and, substantially, unknown.

To acquire information about PIM, a possible way is to perform some measurements over an existing satellite system, i.e. inspecting the received electromagnetic field or performing bit error rate (BER) measurements. These last can be performed only as end-to-end measurements. In both the cases, the problem is the presence of various unexpected effects such as the fading, the multipath, and so on. Thus, a direct characterization of the PIM seems not possible. In similar cases, a feasible way to examine an unknown phenomenon is its reproduction in a laboratory. That requires, in our case, an installation of a complete transmitter in an anechoic chamber and the carrying out of a lot of delicate and accurate measurements. Some technical difficulties appear following this way such as, for example, the real reproduction of the in-service behavior of the transmitter.

Another complementary way is the computer simulation of the whole transmitter output corrupted by the PIM. This is just the way proposed in this paper. Also in this case, however, some hard difficulties appear as we will describe in the following.

In particular, some steps of frequency conversion, decimation, and filtering are required. However, by considering that the third power of the whole signal can be reduced to a sum of cosine functions, we will show that the analysis can be correctly carried out leaving aside frequency range.

2. SOME BASIS PROPERTIES OF GSM

An exhaustive description of the features and characteristics of GSM service can be found in various internet sites, as in [19–21]. Only a brief description will be given here in order to facilitate the understanding of the reported work.

In European Countries, a base station transmits in the 935-960 MHz band and receives in the 880-915 MHz band. So, in our simulations, we suppose that a satellite transmitter, viewed as a base station, would transmit in the 935-960 MHz band. Each transmitted channel operates in a band of 200 kHz. This means that 124 channels can be allocated in the whole band of the transmitter, using the remaining 200 kHz as a separation band with respect to other radio services. A time division multiple access (TDMA) technique is implemented to increase the capacity of the single channel. This further feature of the GSM systems, however, have not implications with the matter of our work, so they will be ignored in the following.

In a mixed environment, in which terrestrial radio bases operate together with a satellite radio base, only some channels should be assigned to the satellite. Indeed, the satellite covers an entire macrocell and this characteristic precludes the reuse of the satellite assigned frequencies by the cells belonging to the satellite covered macrocell. On the other hand, in remote and sparsely populated regions, all the channel frequencies can be assigned to the satellite transmitter. An explicative visualization of the channel configuration at the transmitter output is shown in Fig. 1. The modulation used in GSM systems is the Gaussian Minimum Shift Keying (GMSK). It operates in each channel by two frequencies disposed in the center of the channel band at a frequency distance of 32 kHz. The lower and the upper frequencies represent the digital “zero” and “one”, respectively. The transitions between the two frequencies are disposed in such a way that no discontinuities are introduced in the time behavior of the carrier phase. Therefore, the change of the frequency happens at the zero crossing of the carrier amplitude, as shown in Fig. 2. The speed of the transitions between the lower and the upper frequencies is controlled and reduced by a gaussian filter. In this way, the band occupied during the said transitions is greatly reduced. Obviously, in the receiver demodulator, the decision instant corresponds to the middle of the bit time. In our simulations, since the PIM phenomenon in a first approximation have no memory (as described in the following section), we consider a situation at decision instant, when all the involved frequencies are stabilized.

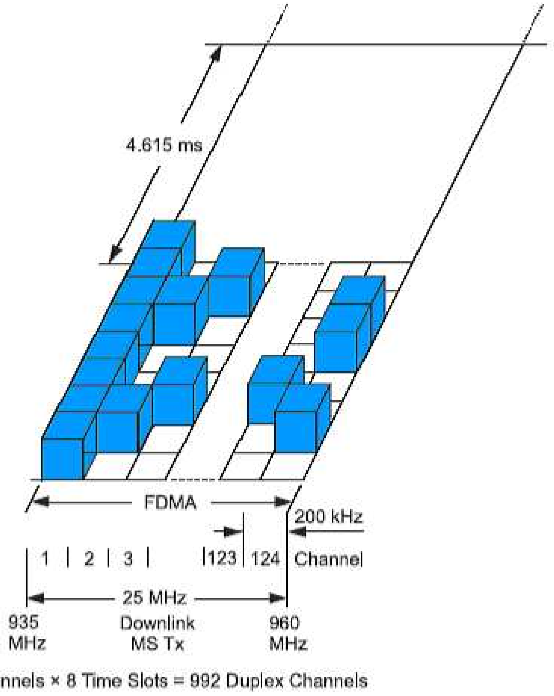

Figure 1. Channel configuration at the transmitter output

3. PASSIVE INTERMODULATION

Intermodulation occurs when two or more sinusoidal signals cross a nonlinear device. The passive components of the final stage of the satellite transmitter can introduce some nolinearities. These nonlinearities can be due to various causes, as:

contact nonlinearities: a thin layer of air between the two

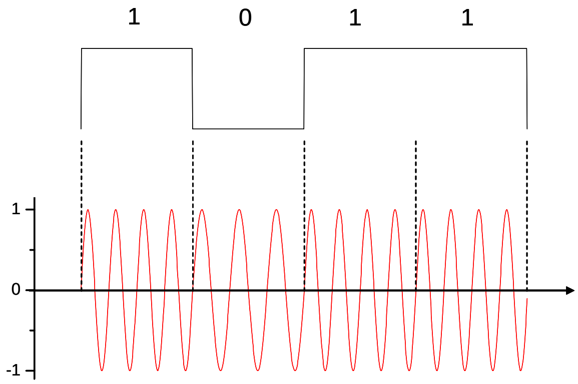

Figure 2. Minimum Shift Keying (MSK) modulation; the further insertion of a Gaussian filter to reduce the occupied bandwidth during the frequency transitions realizes the Gaussian Minimum Shift Keying (GMSK) modulation

metals in part of the contact area can induce discharges; analogously a thin layer of oxide or extraneous material can have a semiconductor-like behavior; a reduction of the contact area due to irregularities of the surfaces of the two sides of the contact can produce intense current densities and induce local thermal variations which in turn induce a nonlinear behavior;
bulk material nonlinearities: microfractures inside the conductor material can produce discharges; ferromagnetic behaviour of the conductors or, especially, of the waveguide material produce nonlinearities;
antenna nonlinearities: imperfections of the surface and the edges of the antenna reflector produce nonlinearities; this is particularly the case of folding antennas;
external metallic masses: when subjected to a strong RF electromagnetic field, these masses can irradiate spurious frequencies.

Further information about this topic can be found in the already cited references [2–12]. The nonlinear relation between input and output of the device can be mathematically represented by a Taylor's expansion:

$$V_{out}(t) = k_1 \cdot V_{in}(t) + k_2 \cdot V_{in}^2(t) + k_3 \cdot V_{in}^3(t) + \cdots \quad (1)$$

This relation represents the PIM effects as memory less ones. This is a reasonable approximation since the reactive effects are very small. A simple illustration of the PIM effects modeled by (1) considers an input signal formed by only two sinusoidal components, namely

$$V_{in} = V_1 \cdot \cos(\omega_1 t) + V_2 \cdot \cos(\omega_2 t). \quad (2)$$

Also in this simple case, a lot of spurious frequencies are generated. The permitted frequencies in the whole spectrum of the unwanted modes are

$$f = \pm m f_1 \pm n f_2 \quad (3)$$

with m and n integer numbers. Obviously, if the PIM effects are small, then the amplitudes of these spurious frequencies are also small and are vanishing when the order $\mathcal{N}$ of the unwanted frequencies increases. This value is given by the expression

$$\mathcal{N} = |m| + |n| \quad (4)$$

In multifrequency environments, the number of intermodulation products rapidly increases with the number of transmission channels [22], as shown in Fig. 3.

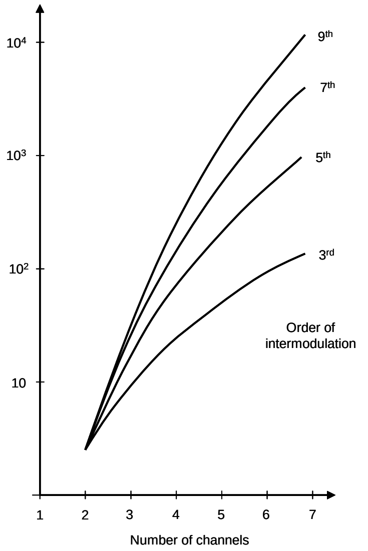

Figure 3. Relationship between the number of channels and the number of intermodulation products

4. STUDY OF THE PIM EFFECTS IN A GSM SATELLITE TRANSMITTER

As described above, a GSM transmitter operates over 124 channels. These channels are uniformly spaced in frequency and each channel uses two frequencies for the GMSK modulation. Also these frequencies are disposed in similar way inside each channel. In order to obtain the simulation of the behavior of the transmitter's output, taking into account the assumption that the PIM effects are memory less, firstly we shall evaluate the whole transmitter output at the instant corresponding to the middle of the bit time. Indeed, this instant, in an ideal GMS communication system corresponds to the decision instant of the receiver demodulator. At this time, all the transmitted frequencies should be stabilized. The possible frequency configurations of the whole output are 2^{124}. It is evident that is not possible and not useful a study of each of these configurations. Thus, our simulation will be restricted to some meaningful configurations. In order to chose them some hypotheses can be done. Firstly, we suppose that in all channels the same symbol (0 or 1) is transmitted. If we suppose the transmission of the symbol "1" for all the channels, the whole output of the PIM-less transmitter assumes the form

$$s(t) = \sum_{k=1}^{N} \cos((\omega_1 + k\,\Delta\omega)t) \tag{5}$$

Because all the transmitted frequencies are uniformly spaced, then also the spurious frequencies induced by PIM result equispaced with a step $\Delta\omega$. To give a simple and synthetic explanation of this property we consider separately the powers of the PIM-affected output signal of the transmitter as approximated by expression (1). Now

$$\begin{aligned} s^2(t) &= \left(\sum_{k=1}^{N} \cos((\omega_1 + k\,\Delta\omega)t)\right)^2 = \\ &= \sum_{k=1}^{N} \cos^2((\omega_1 + k\,\Delta\omega)t) + \\ &+ 2\sum_{k=1}^{N-1} \cos((\omega_1 + k\,\Delta\omega)t) \sum_{h=k+1}^{N} \cos((\omega_1 + h\,\Delta\omega)t). \end{aligned} \tag{6}$$

In order to inspect the frequency behavior of the term $s^2(t)$, let us consider the two terms of the sum in (6) separately.

By $cos^2\alpha = \frac{1+\cos 2\alpha}{2}$, we obtain

$$\cos^2((\omega_1 + k\,\Delta\omega)t) = \frac{1}{2} + \frac{1}{2}\cos((2\omega_1 + 2k\,\Delta\omega)t). \tag{7}$$

Then the terms $\cos^2(\cdots)$ give contributions very far from ω_1. For the other terms, from the expression

$$\cos\alpha\cos\beta = \frac{1}{2}\left(\cos(\alpha - \beta) + \cos(\alpha + \beta)\right), \tag{8}$$

we have

$$\begin{aligned} &\cos((\omega_1 + k\,\Delta\omega)t) \cdot \cos((\omega_1 + h\,\Delta\omega)t) = \\ &= \frac{1}{2}\underbrace{\cos(((k-h)\Delta\omega)t)}_{(*)} + \frac{1}{2}\cos((2\omega_1 + (k+h)\Delta\omega)t). \end{aligned} \tag{9}$$

The term of the third order can be written as

$$\begin{aligned} s^3(t) &= \left(\sum_{k=1}^{N} \cos((\omega_1 + k\,\Delta\omega)t)\right)^3 = s(t) \cdot s^2(t) = \\ &= \sum_{k=1}^{N} \cos((\omega_1 + k\,\Delta\omega)t) \cdot \left[\sum_{k=1}^{N} \cos((\omega_1 + k\,\Delta\omega)t)\right]^2. \end{aligned}$$

Using (6), the previous expression can be written as

$$\begin{aligned} s^3(t) &= \sum_{k=1}^{N} \cos((\omega_1 + k\,\Delta\omega)t) \cdot \\ &\cdot \left\{\sum_{k=1}^{N} \cos^2((\omega_1 + k\,\Delta\omega)t) + \right. \\ &\left. + 2\sum_{\bar{k}=1}^{N-1} \cos((\omega_1 + \bar{k}\,\Delta\omega)t) \cdot \sum_{h=\bar{k}+1}^{N} \cos((\omega_1 + h\,\Delta\omega)t)\right\}. \end{aligned}$$

Let us consider separately the two terms of the previous product.

The first term, considering (7), becomes

$$\begin{aligned} &\sum_{k=1}^{N} \cos((\omega_1 + k\,\Delta\omega)t) \cdot \sum_{k=1}^{N} \cos^2((\omega_1 + k\,\Delta\omega)t) = \\ &= \sum_{k=1}^{N} \cos((\omega_1 + k\,\Delta\omega)t) \cdot \\ &\cdot \sum_{\bar{k}=1}^{N} \left[\frac{1}{2} + \frac{1}{2}\cos((2\omega_1 + 2\bar{k}\Delta\omega)t)\right] = \\ &= \frac{N}{2}\sum_{k=1}^{N} \cos((\omega_1 + k\Delta\omega)t) + \\ &\underbrace{+ \frac{1}{2}\sum_{k=1}^{N} \cos((\omega_1 + k\Delta\omega)t) \cdot \sum_{\bar{k}=1}^{N} \cos((2\omega_1 + 2\bar{k}\Delta\omega)t).}_{\text{2nd}} \end{aligned} \tag{10}$$

By applying (9) to 2nd term and observing that the term $\cos(\alpha + \beta)$ is out of band of interest, we obtain

$$\text{2nd} = \frac{1}{4}\sum_{k=1}^{N}\sum_{\bar{k}=1}^{N} \cos((\omega_1 + (2\bar{k} - k)\Delta\omega)t).$$

The underbraced term denoted as $(*)$ in (9) produces undesired components in base band. They must be deleted through a high-pass filtering process before the frequency conversion in base band of the received signal.

For the higher order terms are substantially valid the same considerations. Moreover, it is evident that all the spurious frequencies are spaced among themselves of the frequency step $\Delta\omega$, that is the same frequency step of the carries, with respect to the frequency reference ω_1.

Figure 4 shows the spurious components due to the first four terms, with the specified coefficients. Figure 5 shows the components before the filtering process, while in Fig. 6 the effect of the filtering of the components of even order before the frequency conversion is shown. Finally, figure 7 shows how many terms produced by the third power of the signal fall in a certain channel. These terms are those that strongly damage the received signal.

5. CONCLUSION

The behavior of the PIM effects in a satellite GSM transmitter has been investigated through a qualitative approach based on theoretical remarks and simulation results. It was evidenced the periodic nature of these effects induced by the periodic structure of the set of carriers of the transmitter. The presence of undesired spurious frequencies inside the transmission band has been illustrated. It was shown also that the

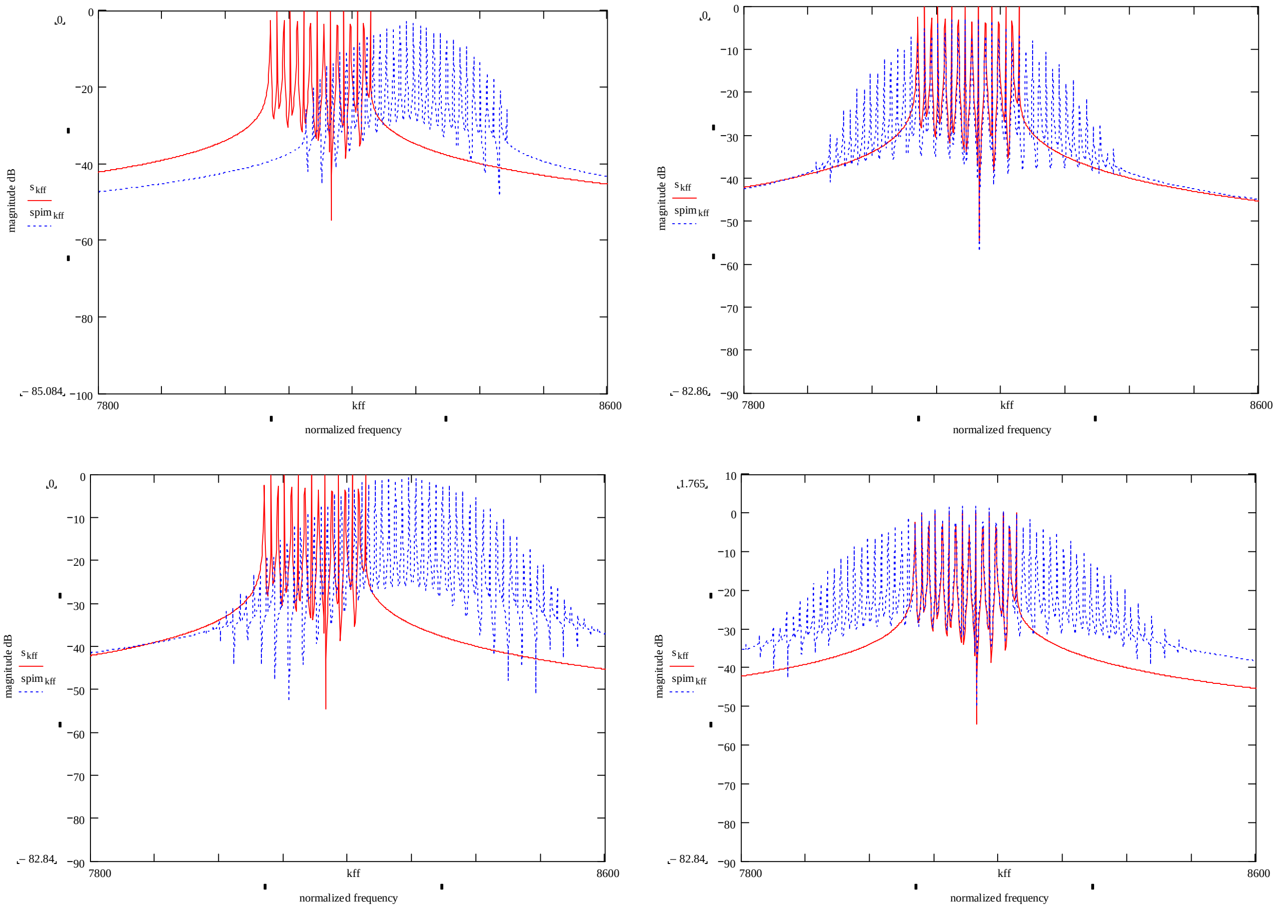

Figure 4. Components due to the 2nd (top-left), 3rd (top-right), 4th (bottom-left), and 5th (bottom-right) term with a coefficient equal to 0.05, 0.005, 0.0005, and 0.00005, respectively (16 channels)

transmitter greatly affects the electromagnetic environment, also in base band.

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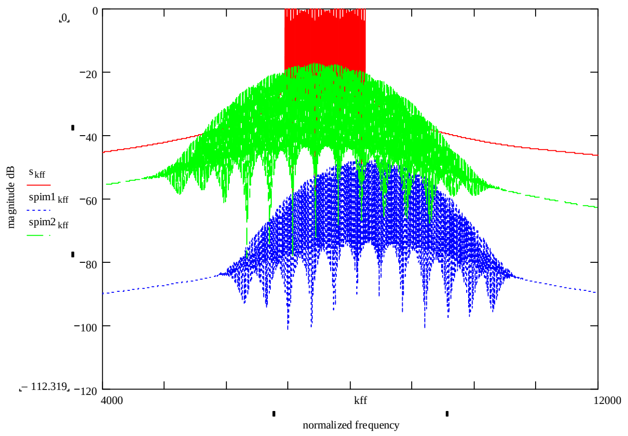

Figure 5. Components before the filtering process

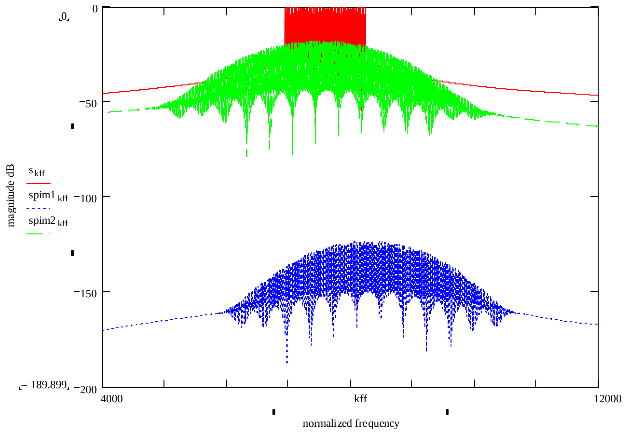

Figure 6. Components after the filtering process

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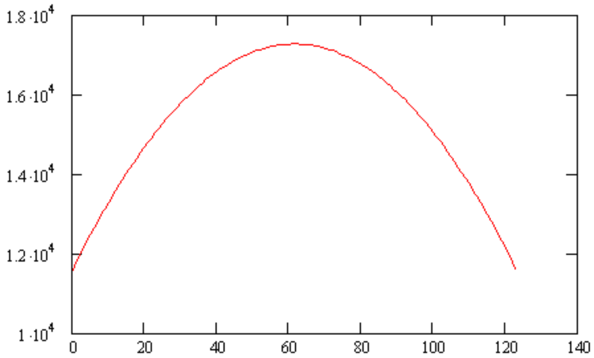

Figure 7. Number of the terms falling in a certain channel k

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