Effect of load impedance on passive intermodulation measurements

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A simple model is derived for predicting the distortion level change of a passive intermodulation source as a function of the impedance loading at the transmitting and intermodulation frequencies. The calculated results correspond well with the measurements, having a mean difference of 0.9 dB.

Introduction: Although known for decades, passive intermodulation (PIM) distortion still remains a problem in many naval, spaceborne, and land communication systems [1, 2]. PIM distortion is caused by small nonlinearities in passive devices such as cables, connectors and antennas [3]. It is especially harmful in systems which incorporate multiple high power transmitting channels and sensitive receivers.

PIM sources, which cause the PIM distortion, are typically highly variable with respect to time and their behaviour may change from sample to sample. Thus, the PIM signal generation can often be considered as a random process. However, some of the complex behaviour of a PIM source can be explained by the behaviour of the loading impedances. It is shown in this Letter, that the impedance loading of a PIM source at the fundamental and intermodulation frequencies may have a large effect on the measured PIM response. A simple Taylor polynomial model and an approximate circuit analysis can be used to predict the frequency and the impedance matching dependency of the reverse and forward PIM level.

Model: To obtain a closed-form expression for the PIM response, some assumptions have to be made. First, the PIM source is assumed to be in series with the signal path and secondly, its impedance is negligible compared with the source and load impedances. These assumptions are valid in most cases since a typical PIM source is a metal junction in the signal path so that, as an intermodulation signal generator, it will be in series with the source and the load. This has also been verified by experiments with PIM near-field scanner measurements [4]. Also, impedance of a metal junction is typically much less than the system impedance. In addition, the distortion level of a PIM source is typically more than 100 dB below the carriers. Therefore, it is assumed that the voltage $v(i(t))$ across the PIM source can be approximated with an Nth order Taylor polynomial

$$v(i) = \sum_{n=1}^{N} a_n i^n, \quad a_n = \frac{v^{(n)}(0)}{n!} \tag{1}$$

where i is the current flowing through the PIM source and $v^{(n)}(0)$ denotes the nth derivative of $v(i)$ at $i = 0$. This approximation implies that the voltage is a smooth function of the current and that the PIM source does not contain any reactive elements. The coefficients a_n are assumed to be constants, i.e. they do not depend on the frequency nor on the source and load impedances.

Consider the circuit diagram in Fig. 1. The forward travelling voltage wave V_{fwd} causes the current I to flow through the PIM source. In this case, two transmitting signals at frequencies f_1 and f_2 are present and the power at the intermodulation frequency $f_3 = 2f_1 - f_2$ is considered. If the impedance of the PIM source is much less than the absolute sum of the source and load impedances, $|Z_s + Z_L|$, the dissipated intermodulation signal power in Z_s is

$$\begin{aligned} P_{rev} &= \frac{1}{2} R_s(f_3) \left| \frac{V(f_3)}{Z_s(f_3) + Z_L(f_3)} \right|^2 \\ &= \frac{9a_3^2}{32} R_s(f_3) \left| \frac{I^2(f_1) I(f_2)}{Z_s(f_3) + Z_L(f_3)} \right|^2 \end{aligned} \tag{2}$$

This will equal the measured reverse PIM power if the insertion loss from the PIM source to the detector is negligible. Anyway, if the insertion loss is known it can be subtracted from (2). The current and the impedances can be expressed with the complex source and load reflection coefficients Γ_s and Γ_L, respectively:

$$I = \frac{V_{fwd}}{Z_0} \frac{1 - \Gamma_L}{1 - \Gamma_s \Gamma_L} \tag{3}$$

$$\frac{1}{Z_s + Z_L} = \frac{1}{Z_0} \left(\frac{1 + \Gamma_s}{1 - \Gamma_s} + \frac{1 + \Gamma_L}{1 - \Gamma_L} \right)^{-1} \tag{4}$$

$$R_s = Z_0 \frac{1 - |\Gamma_s|^2}{|1 - \Gamma_s|^2} \tag{5}$$

where Z_0 is the normalising impedance. These quantities are, of course, dependent on the frequency although not explicitly shown. In many cases, V_{fwd} can be considered as a constant if the output power of the transmitter is kept constant. Otherwise, if there is a frequency dependent component between the duplex filter and the PIM source, the expression for V_{fwd} will contain the insertion loss of that component. The forward PIM level can also be calculated from (2) with the substitution $R_s = R_L$.

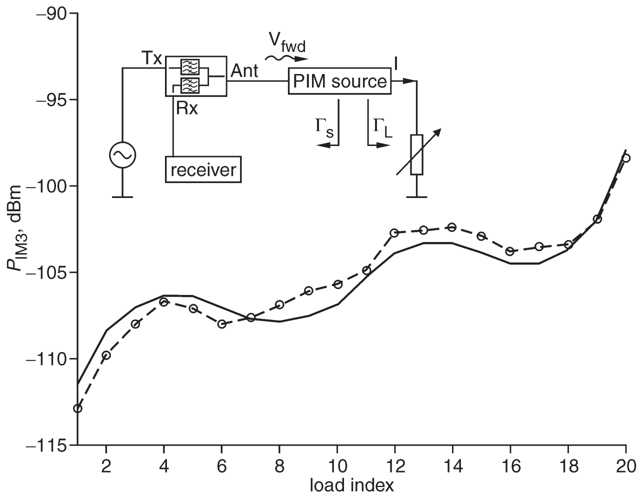

Fig. 1 *Measured and calculated reverse PIM level against load impedance index, typical case*
$0.05 \le |\Gamma_L| \le 0.3$
——— calculated
- -○- - measured
Inset: Circuit diagram

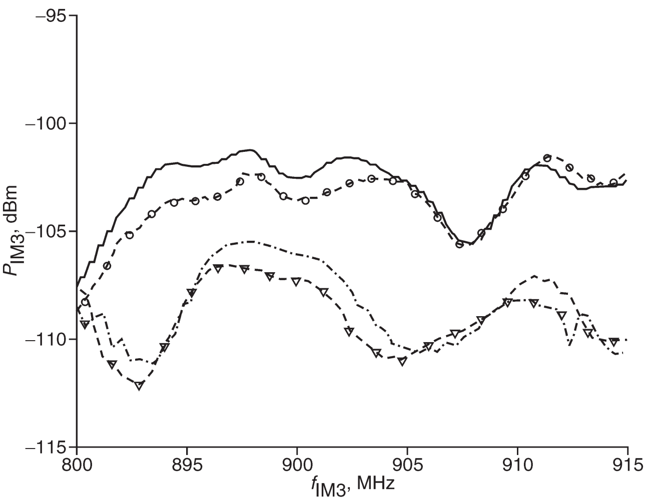

Fig. 2 *Measured and calculated reverse PIM level against frequency,* $f_{IM3} = 2f_1 - f_2$, *typical case*
$|\Gamma_L|$ mainly below 0.18
——— $f_1 = 925$ MHz, calculated
- -○- - $f_1 = 925$ MHz, measured
· - · $f_2 = 960$ MHz, calculated
- -▽- - $f_2 = 960$ MHz, measured

Measurements: A stable PIM source with different load impedances was used to validate the proposed model. An N – N-adapter was the PIM source and three different terminations were used: a broadband resistive load, a dual-band antenna, and a duplex-filter with a matched load. In addition, a microstrip line with a movable PTFE slab below the strip was connected between the PIM source and the termination. This way, the reverse PIM level of the source was measured with 50 different load impedances over the GSM900 frequency band. $|\Gamma_L|$ varied between 0 and 0.33 and the transmitting power was $2\times$ 43 dBm. The residual PIM level of the test setup was below -117 dBm.

The maximum difference between the measured and calculated results, $|P_{calc} - P_{meas}|$, was 4.3 dB, whereas the mean difference was 0.9 dB. Typical plots of measured and calculated results are shown in Figs. 1 and 2, where the reverse PIM level is plotted against different load impedances and against frequency, respectively. Third-order Taylor polynomial was used in the calculations and the unknown constant, a_3, was found by fitting (2) to the measurement results. V_{fwd} was assumed constant.

The largest source of uncertainty in the measurements was the residual PIM level of the equipment. PIM signals that cause the residual intermodulation level may add to the actual measured PIM source signal in-phase or out-of-phase depending on the electrical distances between the sources [5]. The estimated uncertainty due to the residual intermodulation was ± 2 dB. Other error sources were the instability of the PIM source and the frequency dependence of V_{fwd}.

Discussion: The expression for P_{rev} simplifies considerably if Γ_L and Γ_s are assumed to be frequency independent: when the source is matched, P_{rev} will be proportional to $|1-\Gamma_L|^8$, and when the load is matched, P_{rev} will be proportional to $1-|\Gamma_s|^2$. Likewise, P_{fwd} will be proportional to $(1-|\Gamma_L|^2)\cdot|1-\Gamma_L|^6$ and $|1-\Gamma_s|^2$, when the source and load are matched, respectively. Thus, it can be seen that the measured reverse PIM level is strongly dependent on the load matching whereas the source matching is less important provided V_{fwd} is kept constant.

Naturally, components such as antennas and filters are strongly frequency-dependent and the approximations in the previous paragraph do not hold, but still they can be used to estimate the maximum deviation of the PIM response. For example, consider an outdoor base station antenna with $VSWR = 1.3$ and its connector as the main PIM source. Then, the maximum change in the reverse PIM level can be 9 dB as the frequency or the electrical length between the connector and the actual antenna changes.

Conclusion: A simple quantitative model has been developed and verified by experiments to explain the effect of the load impedance on PIM measurements. The calculated values agree well with the measurements having a mean difference of 0.9 dB. It is shown that the load reflection coefficient at the transmitting and intermodulation frequencies may have a large effect on the measured PIM level. These results can be utilised both in PIM measurements as well as in the design of low-PIM devices.

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