Measurement of Radio Receivers' Front-End Nonlinearity by the Frequency Slipping Technique

Vladimir Mordachev, Eugene Sinkevich
EMC R&D Laboratory
Belarusian State University of Informatics and Radioelectronics
Minsk, Belarus
emc@bsuir.by

***Abstract* — An incremental technique for measuring the power transfer characteristic of the radio receivers' input units is proposed. The technique is useful in frequent cases when this characteristic can not be measured directly because of the distortions introduced by the receiver's back-end nonlinearity and by the automatic gain control. To avoid those distortions, the level of the intermediate frequency output signal is maintained constant during the measurements (which is reached by tuning the test signal out from the receiver's working frequency simultaneously with increasing the test signal level). Experimental results illustrating the efficiency of the proposed technique are given.**

***Keywords* — radio receiver, front-end nonlinearity, power transfer characteristic, desensitization.**

I. INTRODUCTION

Radio receiver's operability in severe electromagnetic environment is appreciably defined by its front-end nonlinearity (which is a main cause of intermodulation, cross-modulation, desensitization, etc.) [1], [2]. The front-end nonlinearity is a cumulative nonlinearity of the input radio-frequency (RF) cluster formed by the set of receiver units at its antenna input. In receivers of various complexity, such cluster may include one (RFA or mixer) or several input units operating at radio- and/or intermediate frequency (IF). In many cases, the RF cluster includes all units from the antenna input to the input of the lumped frequency selectivity filter (LFSF) at the penultimate or last IF.

The receiver's front-end nonlinearity can be estimated directly: *1)* by measurement of the power transfer characteristic (PTC) for the whole RF cluster or *2)* by measurement of PTCs for the separate units forming the cluster and subsequent calculation of the aggregate PTC.

However, the direct measurement may suffer from the essential inaccuracy or it may be impossible in principle by the following reasons:

1) In many cases, the input part of receiver is produced as a single component having only the RF input and the output of the last IF path (but LFSF input and, a fortiori, inputs/outputs of separate stages are inaccessible). Unfortunately, this output can not be used for the measurement: if we use it, the saturation area of the measured PTC would be caused by the automatic gain control (AGC) and by the nonlinearity of the last IF path (i.e., the information about the front-end nonlinearity would be lost).

2) Even if the RF cluster output is accessible for connection and measurement, the saturation area of the resulted PTC is still caused by the AGC, so the information about the front-end nonlinearity is lost. Many receivers do not provide the possibility to turn off the AGC.

3) Even if the RF cluster output is accessible for connection and the AGC is turned off, the measured PTC may be corrupted by the change in the RF cluster load impedance due to connection of the measuring equipment.

In this paper, a frequency slipping technique for indirect measurement of receiver's front-end nonlinearity is proposed. Because the receiver response is taken at the output of the last IF path and the influence of AGC is avoided, the technique is applicable in cases when the PTC of the input RF cluster can not be measured directly.

The paper is organized as follows. The main principles of the frequency slipping technique are described in Section II. An example of the technique application is given in Section III: we measured the front-end nonlinearity of the professional high-quality receiver. The main features of the presented technique are briefly summarized in Conclusion.

II. PRINCIPLES OF THE FREQUENCY SLIPPING TECHNIQUE

The main idea of the frequency slipping technique is as follows. In order to avoid the distortions caused by the receiver's back-end nonlinearity and AGC, the level of the intermediate frequency output signal is maintained constant (which is below the threshold of AGC) during the measurements. This is reached by tuning the test signal out from the receiver's working frequency simultaneously with increasing the test signal level.

The frequency slipping technique is implemented by the following algorithm (Fig. 1):

Step 1. Feed the receiver input with a test signal at the receiver's tuning frequency f_0 and at the power level of the receiver's sensitivity P_{in0}, so the nominal level P_0 of the receiver output signal is established.

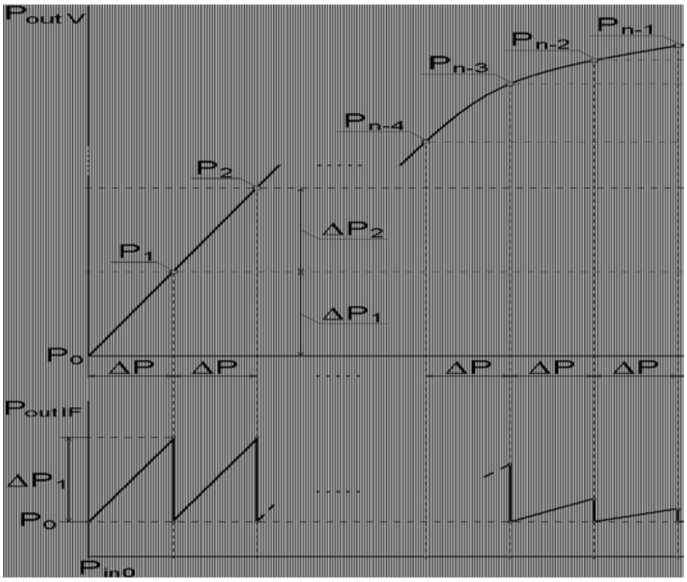

Fig. 1. The main procedures of the frequency slipping test technique

Step 2. Increase the input test signal level by ΔP ($\Delta P \approx 0.5...2$ dB) and measure the corresponding increment ΔP_1 in the output signal level above the nominal value P_0.

Step 3. In order to return the receiver output signal level to the nominal value P_0, tune the input test signal to the neighboring frequency f_1. We call this process as a "slipping" of the test signal on the amplitude-frequency characteristic (AFC) of the receiver's LFSF (the right curve in Fig. 1)

Steps 4 … 2n+1. Pairwise multiple iteration of steps 2 and 3, i.e., consecutive measurement of increments ΔP_2, …, ΔP_{n-1}, ΔP_n in the receiver output signal level above P_0 at each even step, and increasing the difference between the test signal frequency and the receiver's tuning frequency (setting up frequencies f_2, …, f_{n-1}, f_n in order to return the receiver output signal level to value P_0 by "frequency slipping") at each odd step.

Having measured the consecutive increments ΔP_1, ΔP_2, …, ΔP_n in the level of the receiver output signal, which are caused by the fixed increments ΔP in the level of the receiver input signal, we estimate the virtual PTC $P_{out\,V}(P_{in})$ of the receiver as

$$P_{in,k} = P_{in0} + k \cdot \Delta P, \quad (dBm), \quad k = 0, 1, ..., n; \tag{1}$$

$$P_k \equiv P_{out\,V}(P_{in,k}) = P_{k-1} + \Delta P_k, \quad (dBm), \quad k = 1, 2, ..., n. \tag{2}$$

By the virtual PTC (ref. the top curve in Fig. 1), we mean the receiver's PTC (from its antenna input to the output of the last IF) that would be observed if the receiver's output part (from the LFSF input to the output of the last IF) is perfectly linear. Hence, the virtual PTC of the receiver $P_{out\,V}(P_{in})$ is proportional to the PTC $P_{out\,FE}(P_{in})$ of the input RF cluster:

$$P_{out\,V}(P_{in}) = P_{out\,FE}(P_{in}) + G_{0\,IF}, \quad (dBm), \tag{3}$$

where $G_{0\,IF}$ is a small-signal gain of the receiver's output part

The basic assumption of the frequency slipping technique is that the input RF cluster has flat frequency response within the frequency span from f_0 to f_n. So, the band of the frequency slipping should be chosen in such a manner that this assumption is fulfilled (ref. Section III for the example).

III. VALIDATION OF THE FREQUENCY SLIPPING TECHNIQUE

By the instrumentality of the double-frequency test system (the options of which implement both traditional and frequency-slipping techniques of PTC measurement) [3], we investigated the front-end nonlinearity of the professional high-quality receiver used in modern radio monitoring and spectrum management systems.

The analyzed mode of operation of this receiver under test (RUT) has the following main features. There are three conversions of frequency; the main frequency selectivity is implemented in the third intermediate-frequency path (IF3, 455 kHz), however the additional LFSF is also present at the second intermediate frequency (IF2, 45 MHz); frequency bandwidths are 2 MHz at IF2 and 120 kHz at IF3. AGC (autoranging) is implemented and it can be turned off.

The RUT's AFC measured at IF2 output is given in Fig. 2. The central part of this AFC is formed by the LFSF located in the IF2 path, the disturbances in periphery parts of this AFC are caused by the spurious responses of the RUT. The analysis of this characteristic allows one to assume the ability of suppression of the test signal level at least 80 dB by the frequency slipping on the right branch of the IF2-located LFSF's AFC.

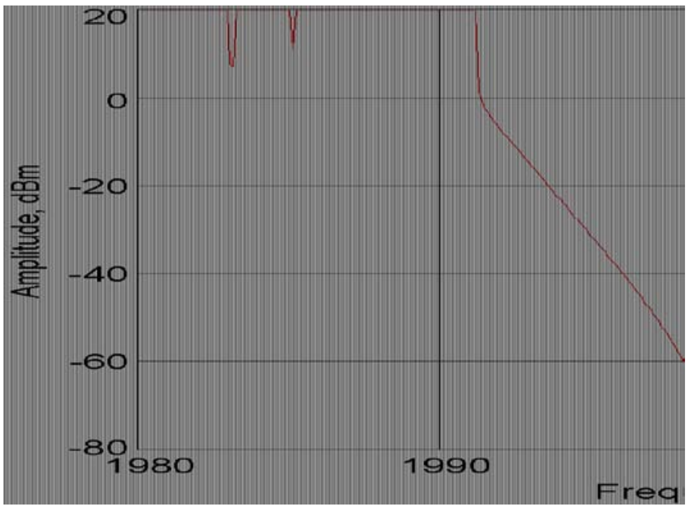

Fig. 2. Amplitude-frequency characteristic (AFC) measured at IF2 output: RUT tuning frequency is 2 GHz, IF2 bandwidth is 2 MHz

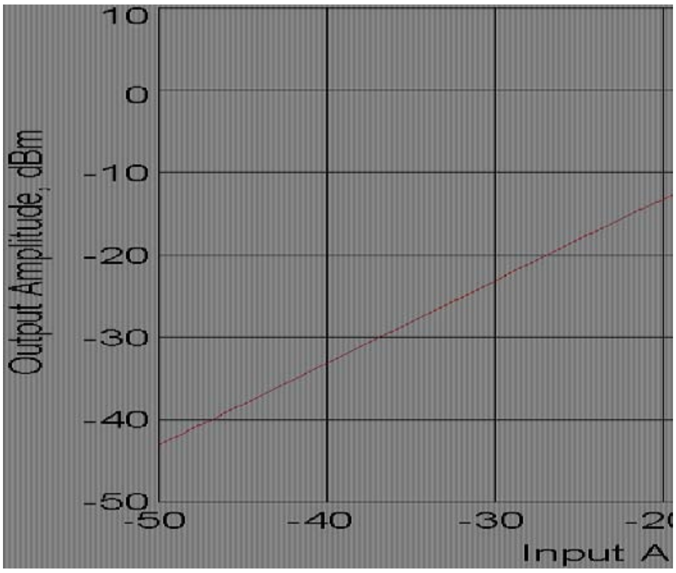

Fig. 3. Power transfer characteristic (PTC) measured at IF2 output by the traditional technique (at the tuning frequency of the RUT)

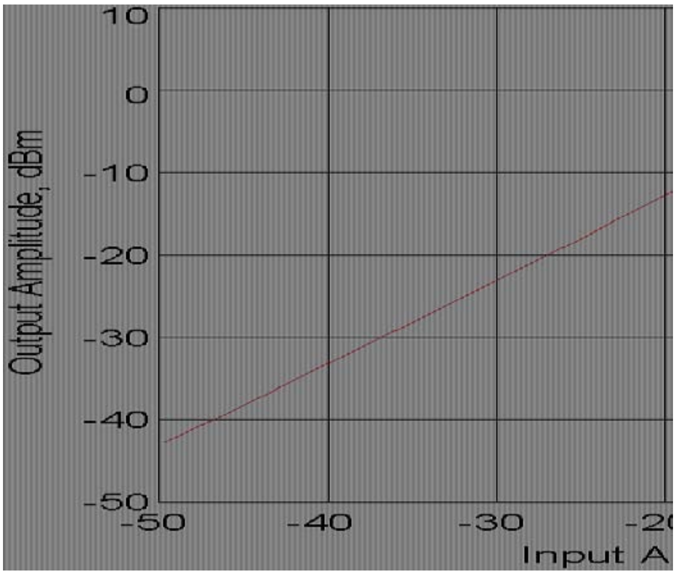

Fig. 4. Power transfer characteristic (PTC) measured at IF2 output by the frequency slipping technique

The PTC measured at IF2 output by the traditional technique (i.e., at the RUT's tuning frequency of 2 GHz) is shown in Fig. 3: the small-signal gain is equal to 7 dB, the nonlinear area begins at the input test signal level of -16 dBm, the 1-dB compression point is -12 dBm, and the deep saturation is observed above 0 dBm.

The virtual PTC measured at IF2 output by the frequency slipping technique (the band of the frequency slipping is about [2000; 2012] MHz) is presented in Fig. 4: the area of deep saturation is also observed, but the nonlinear area begins at the input signal level of -3 dBm (i.e., 13 dB later than in Fig. 3).

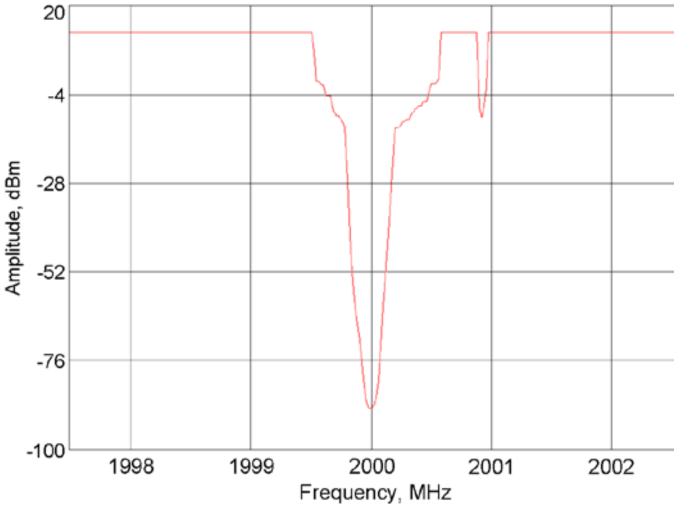

Fig. 5. Amplitude-frequency characteristic (AFC) measured at IF3 output: RUT tuning frequency is 2 GHz, IF3 bandwidth is 120 kHz

This difference characterizes the contribution of the back-end (IF2-path after LFSF) nonlinearity into the aggregate PTC of the RUT. The 1-dB compression point of the virtual PTC (which is equal to 1 dBm in Fig. 4) approximates the susceptibility of the RUT to desensitization.

The results of similar measurements at IF3 output in the same conditions (RUT settings are not changed) are given in Figs. 5, 6, and 7. The input-referred dynamic range of the measurements is 95 dB. The traditional PTC has the small-signal gain of 52.5 dB and a sharp knee (ref. Fig. 6): the nonlinear area begins at -62 dBm, the 1-dB-compression point is -61 dBm, and the deep saturation is observed above -58 dBm. The frequency slipping is performed in [2000; 2000.5] MHz band at the right branch of the IF3-path-located LFSF (ref. Fig. 5). The shape of the resulted virtual PTC in Fig. 7 is more complicated (as compared to Fig. 4): the nonlinear area begins at -25 dBm, then a 1-dB-expansion point (which is caused by the measurement error – ref. below) is observed at -21 dBm, after that, the characteristic has the 1-dB-compression point at -8 dBm and the deep saturation area above -8 dBm. The 53 dB difference between the 1-dB compression points in Figs. 7 and 6 is achieved.

Applying the general equation (3) to the virtual PTC $P_{IF3\,out\,V}(P_{in})$ measured at IF3 output (ref. Fig. 7), we get

$$P_{IF3\,out\,V}(P_{in}) = P_{IF2\,out}(P_{in}) + G_{0\,IF3}, \quad (dBm)\,, \qquad (4)$$

where $P_{IF2\,out}(P_{in})$ is the traditional PTC measured at IF2 output (ref. Fig. 3) – this PTC is now considered as the front-end PTC $P_{out\,FE}(P_{in})$ because the frequency slipping band of [2000; 2000.5] MHz is not affected by the IF2-located LFSF (ref. Fig. 2) and, therefore, the saturation is observed in the last stages of IF2 path. $G_{0\,IF3}$ is the small-signal gain of the receiver's IF3 path – this gain can be computed as a difference between the linear gains of the traditional PTCs given in Figs. 3 and 6: $G_{0\,IF3} = 52.5 - 7 = 45.5$ dB.

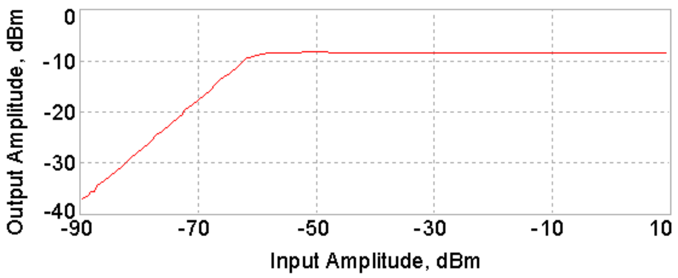

Fig. 6. Power transfer characteristic (PTC) measured at IF3 output by the traditional technique (at the tuning frequency of the RUT)

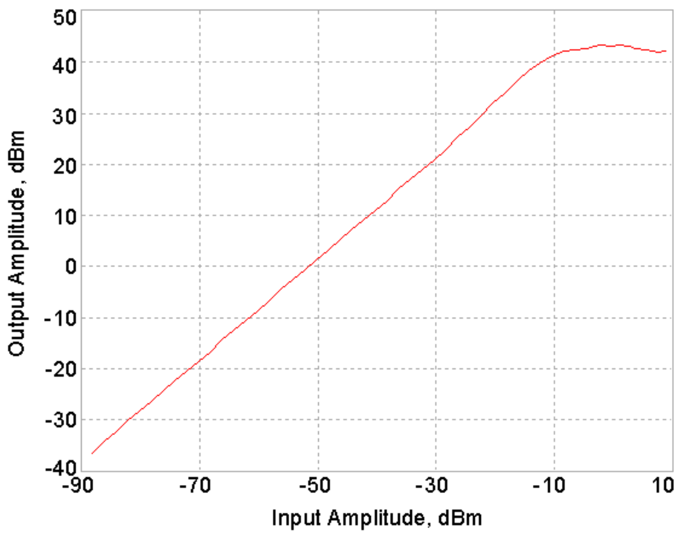

Fig. 7. Power transfer characteristic (PTC) measured at IF3 output by the frequency slipping technique

As follows from the comparison between the measured virtual PTC (ref. Fig. 7) and its theoretical estimation by formula (4), the error in measurement by the frequency slipping technique has in this case the following values: less than 1 dB in the linear area, 1…2 dB in the "knee" area, and 2…4 dB in the saturation area. The error accumulation with increasing the input signal level is caused by the recurrent structure of the algorithm – ref. formula (2). The error may be reduced by the following ways:

- increase the accuracy of the power measurements (e.g., by increasing the measurement time);
- increase the nominal level P_0 of the output signal, but keep it within the linear area of the traditional PTC (e.g., use $P_0 = -20$ dBm for the measurements at IF3 output – ref. Figs. 6 and 7).

IV. Conclusion

The frequency slipping technique makes it possible to measure the receiver's front-end PTC so that the influence of the receiver's back-end nonlinearity and AGC is avoided. That is why the technique is useful in frequent cases when the direct or elementwise measurement of the front-end PTC is unrealizable. The technique can be applied to receivers with different kinds of the back-end nonlinearity (e.g., to a radar receiver which has the logarithmic PTC for the echo signal path).

The application of the frequency slipping technique is limited in the following sufficiently rare cases:

- if the AGC's control signal is taken before LFSF, i.e., feed-forward AGC is implemented (for protection from the out-of-band interference) [6], [7], [8];
- if the automatic control of the IF bandwidth is implemented in the receiver [6];
- if the maximum attenuation of the frequency-slipping test signal in the receiver's LFSF is less than the dynamic range of the receiver's input units.

In all other cases the virtual PTC measured by the frequency slipping technique makes it possible to estimate the susceptibility of the receiver to adjacent-channel nonlinear effects (intermodulation, cross-modulation, desensitization). E.g., the input-referred 1-dB compression point of the virtual PTC may be used as a coarse estimation of the desensitization susceptibility. For more accurate estimation, a high-order polynomial model of the front-end nonlinearity may be extracted from the virtual PTC by the technique described in [4]. This model may be used to simulate the receiver's operation in presence of high-level out-of-band signals by the instrumentality of the discrete nonlinear analysis technology and software [5].

The frequency slipping technique is recognized to be useful, and it is implemented as an option of the double-frequency test system [3].

References

[1] A handbook series on electromagnetic interference and compatibility, Vol.7: Duff W.G. Electromagnetic compatibility in telecommunications. Interference Control Technologies, Inc., Gainesville, VA, 1988.

[2] Rohde U.L., Whitaker J. Communications Receivers: DSP, Software Radios, and Design, 3rd Edition, McGraw-Hill, New York, 2000.

[3] Mordachev V.I., Sinkevich E.V. "Experimental Analysis of Radio Receiver Susceptibility to Out-of-Band Interference by Means of Double-Frequency Test System", Proceedings of the 10-th Int. Symp. on EMC "EMC Europe 2011", UK, York, Sept. 26-30, 2011, pp. 405-411.

[4] Sinkevich E.V. "AM-PM Conversion Simulation Technique for Discrete Nonlinear Analysis of Electromagnetic Compatibility", Proceedings of the VIII-th Int. Symp.on Electromagnetic Compatibility and Electromagnetic Ecology, Saint-Petersburg, Russia, June 16-19, 2009, pp.127-130.

[5] "EMC-Analyzer. Mathematical models and algorithms of electromagnetic compatibility analysis and prediction software complex", Minsk, 2012.

[6] Palshkov V. Radio Receivers, "Radio I Swiaz", Moscow, 1984.

[7] Alegre J.P., Calvo B., Celma S. "A Low-Voltage High-Performance CMOS Feedforward AGC Circuit for Wideband Wireless Receivers", ETRI Journal, Vol. 30, No. 5, Oct. 2008, pp. 729-734.

[8] Perez J.P.A., Pueyo S.C., Lopez B.C. Automatic Gain Control: Techniques and Architectures for RF Receivers, Springer, New York, 2011.