Effect of RF Receiver Nonlinearity on Mobile Telecommunication Systems

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Abstract – **This paper proposes a modified model of signal-to-interference-and-noise ratio (SINR) which include the interference due to intermodulation products. Using this model, we study the effect of receiver's nonlinearity on the performance of telecommunication systems. We examine the problem of interference caused by intermodulation products generated by unwanted interference signals at receivers. Specifically, third-order intermodulation distortion (IMD3) that could be at frequencies within working band and drive circuits into saturation causing blocking for wanted signal at same frequency. Using Matlab software and nonlinear amplifier model, we achieve a practical calculations for third-order intercept point (IP3). Effect of Intermodulation products on SINR is shown using the third-order input intercept point (IIP3) specifications for GSM receiver and SINR modified model and Matlab software.**

Keywords – **SINR, GSM, RF receiver, Nonlinearity, Intermodulation.**

I. INTRODUCTION

In according to manage the increasing in the number of mobile subscribers around the world and their demands, more operators and base stations and frequencies reuse should be achieved. Which lead to a diverse range of challenges in frequency planning. Most important one is intermodulation because - as an example - third-order intermodulation products generated by two GSM-1800 signals could fall in UMTS band and interfere with one UMTS signal [1]. Thus, although mobile stations receive desired signals only from their operating base station, high-power signals from the neighboring base stations for another service providers, regardless of their carrier frequencies, may cause desensitization and blocking by forcing their circuits into saturation.

The intermodulation in mobile nonlinear systems can generate two different types of interference: the one that is called in-band, that is generated inside the GSM-900, GSM-1800 or UMTS band and is derived from inside frequencies, and the out of band interference that is generated mixing terms from the GSM-900, GSM-1800 or UMTS band [1].

The most problematic of all the intermodulation distortions are third-order intermodulation products with frequencies $2f_a - f_b$ and $2f_b - f_a$. This is because when the difference between f_a and f_b is small, the intermodulation products fall in-band close to the fundamentals. If the fundamentals at frequencies f_a and f_b are two strong interfering signals, they could produce third-order intermodulation products within the low-noise amplifier of the victim receiver and corrupt the desired signal. The performance metric that characterizes nonlinear devices for such third-order intermodulation products is the “third-order intercept point” (IP3) [2].

In this paper, we use modified model of signal-to-interference-and-noise ratio (SINR) which include the interference due to intermodulation products which could be generated due to receiver nonlinearity. This modified model could be used to analyze receiver nonlinearity characteristic to minimize intermodulation products effect, on the other hand it could be used to modify mobile networks planning technique and frequency allocation algorithms to avoid generating these unwanted interference signals beside of receiver nonlinearity. We use Matlab software to achieve a practical calculations for third-order intercept point (IP3) and effect of intermodulation products on SINR.

II. SINR MODELS

The signal-to-interference-and-noise ratio is defined as the power of a certain signal of interest divided by the sum of the interference power (from all the other interfering signals) and the power of noise all at the output of receiver. In the mobile telecommunication systems standard SINR ($SINR^s$) is widely used to calculate signal-to-interference-and-noise ratio [4] [5] [6].

$$SINR^s = \frac{P_{signal}}{N + P_{interference}} \qquad (1),$$

where P_{signal} and N are respectively the desired signal and thermal noise power at the receiver, while $P_{interference}$ is interference power form all external interference resources.

Practically, the most studied interference in the cellular mobile systems are co-channels and adjacent channels interference. This lead to the enhanced SINR model ($SINR^e$) which take into account these two main source of interference.

$$SINR^e = \frac{P_{signal}}{N + \sum_i P_i} \qquad (2),$$

where P_i is the power of i^{th} co-channel and adjacent channel interfering signals. The received signal power P_{signal} and P_i could be calculated using one model for signal propagation and path loss. There are many models for co-channel and adjacent channel interference available to use [7] [8].

Standard and enhanced SINR models are used to estimate performance of wireless networks. But these models not

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considering probability of interference due to nonlinearity of RF receiver. Intermodulation products generated in nonlinear stages in receiver such as mixers and amplifiers could cause interference with the desired signal and therefore should be included.

III. Analysis Of Intermodulation Interference

A. Intermodulation Modeling

Intermodulation products are produced when two or more in-band signals as given in Eq. (3) are applied to the input of a nonlinear receiver has transfer function given in Eq. (4) , these signals mix within the receiver and they form new components that are not harmonics of the input frequencies. These components are termed as intermodulation distortion products, as shown in Fig.1 [2] [9].

$$x = a\cos 2\pi f_a t + b\cos 2\pi f_b t \quad (3).$$

$$y(t) = \sum_{i=0}^{n} k_i * x(t)^i \quad (4).$$

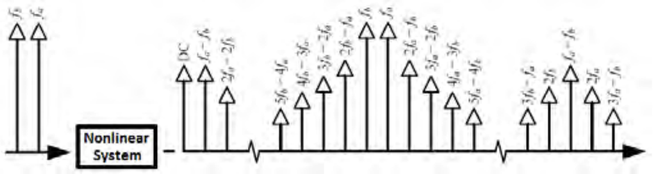

Fig.1. Even and odd-order intermodulation products.

The nth order intermodulation product is given at frequency $\pm n_a f_a \pm n_b f_b$ *where* $|n_a| + |n_b| = n$. The transfer function order could be limited to 3, because the higher order products are of less significance.

In this paper, we consider only the products at frequencies $2f_1 - f_2$ and $2f_2 - f_1$ which are commonly referred as third-order intermodulation distortion (IMD3) products. If the distance between the frequencies of two in-band interferers (f_1 and f_2) is similar to the distance between one of the interferers and the useful signal at f_0, one of the resulting intermodulation products may fall close or within the receiver channel and may corrupt the desired signal. The IMD calculation method based on intercept points is as follow [3]:

When two incoming signals with frequencies at f_1 and f_2 interact, only two third-order intermodulation products of type IM3(2,1) are possible. In case of three signals with frequencies at f_1, f_2 and f_3, intermodulation products of types IM3(2,1) and IM3(1,1,1) are possible. IM3(2,1) and IM3(1,1,1) products frequencies f_{IMD} are as given in Eqs. (5) and (6) respectively.

$$f_{IMD} = 2f_a \pm f_b \quad (5).$$

$$f_{IMD} = f_a \pm f_b \pm f_c \quad (6),$$

where $a, b, c \in \{1,2,3\}$ and $a \neq b \neq c$.

Power of intermodulation product IM3(2,1) can be calculated by:

$$P_{IMD-2} = 3(P_{e-in} + G_{RX}) - 2OIP_3 \quad (7),$$

where P_{IMD-2} is output power of the third-order intermodulation product IM3(2,1) in dBm, OIP_3 is 3rd order output intercept point of the receiver in dBm, G_{RX} is receiver gain in dB and P_{e-in} is input power of incoming signal into the receiver in dBm.

$$P_{e-in} = (2P_1 + P_2)/3 \quad (8),$$

where P_1, P_2 are powers of incoming signals at frequencies f_1, f_2 correspondingly. Power of intermodulation product IM3(1,1,1) can be calculated by :

$$P_{IMD-3} = 3\,(P_{e-in} + G_{RX}) - 2OIP_3 + 6 \quad (9),$$

where P_{IMD-3} is output power of the third-order intermodulation product IM3(1,1,1) in dBm. P_{e-in} in this situation is given by:

$$P_{e-in} = (P_1 + P_2 + P_3)/3 \quad (10),$$

where P_1, P_2, P_3 are powers of incoming signals at frequencies f_1, f_2, f_3 correspondingly.The equivalent intermodulation product level recalculated to the input of the receiver P_{in-IMD} (dBm) is equal to:

$$P_{in-IMD} = P_{IMD} - G_{RX} \quad (11).$$

Or it could be calculated by:

$$P_{in-IMD} = 3\,P_{e-in} - 2IIP_3 + 6 \quad (12).$$

Interferences caused by intermodulation products in the receiver occur when the following two conditions are fulfilled:

$$F_R - 0.5B_{IF} \leq f_{IMD} \leq F_R + 0.5B_{IF} \quad (13).$$

and

$$SIR < A \quad (14),$$

where F_R is tuning frequency of the receiver, B_{IF} is passband value of the IF stage or based band filter bandwidth if there is no IF stage and A is co-channel protection ratio.

B. Modified SINR model

As shown in Fig.2, intermodulation products create unwanted components at frequencies which may interfere with the desired signal. In a worst case, the IMD3 product will fall directly into the desired channel (similar to co-channel interference). With increasing of the frequency offset between the IMD3 product and the desired signal, their impact to SINR becomes less harmful (similar to adjacent channel interference). Modified model of SINR will include the interference due to third-order intermodulation distortion (IMD3) products and is given by Eq. (15).

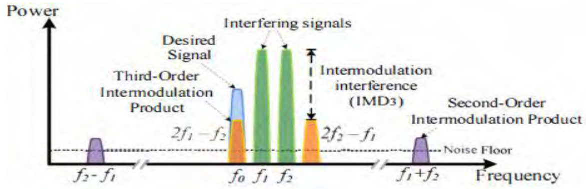

Fig.2. Third-order intermodulation distortion causing interference in the desired channel of a receiver.

$$SINR^m = \frac{P_{signal}}{N + \sum_i P_i + P_{IMD3}} \qquad (15),$$

where P_{IMD3} represents interference power caused by third-order intermodulation distortion and it can be expressed by:

$$P_{IMD3} = \sum_k \sum_j P_{IMD-2} + \sum_k \sum_j \sum_l P_{IMD-3} \qquad (16),$$

where $k \neq j \neq l$ are the number of frequencies used in the telecommunication system and f_k, f_j, f_l are the signals which produce components with frequency equal to f_{IMD} as given in Eqs. (5) and (6) and this f_{IMD} is achieve the condition in Eq.(13) or it shouldn't be taken into account. In mobile telecommunication systems, there are many ways to minimize interference due to co-channel and adjacent signals during frequency planning such sectoring and cell-splitting and that will increase $SINR^e$ [8] [10]. In this paper we consider interference generated just form intermodulation products, so modified model of SINR can be expressed as:

$$SINR^m = \frac{P_{signal}}{N + \sum_k \sum_j P_{IMD-2} + \sum_k \sum_j \sum_l P_{IMD-3}} \qquad (17).$$

IV. Third-Order Intercept Point IP3 Calculation Using Matlab Software

We calculate third-order intercept point for nonlinear system such as nonlinear amplifier by using simple model as in Fig.3 with two signals with frequencies (990 ,1010 MHz), considering amplifier with gain 0 dB and noise figure 3.01 dB. We use spectrum analyzer at the input and the output of amplifier to measure the power of the fundamental signal and power of third-order product signal.

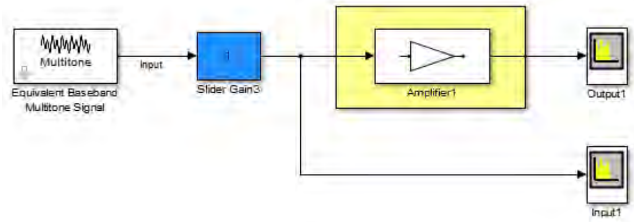

Fig.3. Matlab model for practical calculation.

To achieve that there are two options:

Use two signals at equal level: The power of input signals is equal and range between $(-27{\sim}\,48\,)dBm$, by using spectrum analyzers to measure powers at the output, the IP3 could be shown in Fig.4.

Use two signals at different level: Power of the first input signal will be constant at 5 dBm, and the second input signal power will range from $-37 dBm$ to 49 dBm, and with spectrum analyzers measure output powers for the fundamentals signals and third-order intermodulation product. But here to have a correct calculation, the equivalent input and output power are calculated by using Eq. (8). Then by plotting fundamental equivalent signal with third-order intermodulation product, in Fig. 5, could be found that IP_3 is equal to 30 dBm.

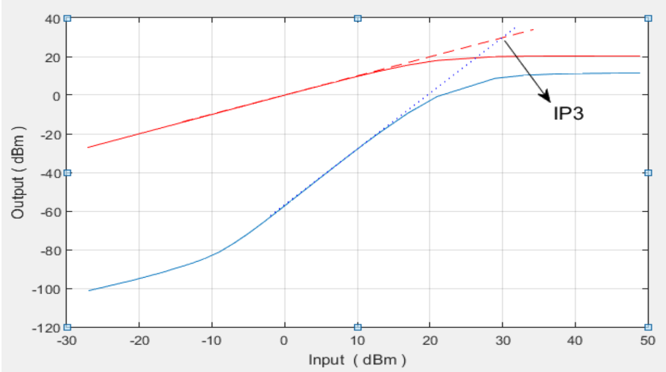

Fig.4. Practical Measurements 1. (blue line for the third intermodulation product)

As shown in Fig.5 the third-order intercept point IP_3 is equal to 30 dBm.

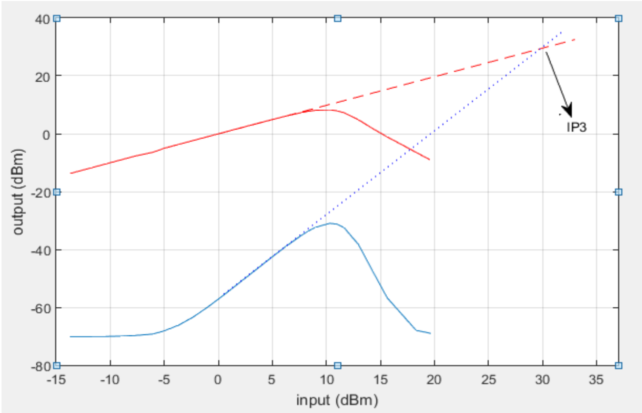

Fig.5. Practical measurements 2. (blue line for the third intermodulation product)

V. Simulation Results Using Modified SINR Model

For GSM receiver with noise floor $N = -111\ dBm$, the minimum SINR value required for GSM receiver is 9 dB. That's mean for desired signal at $-99\ dBm$, if the third-order input intercept point is $IIP = -18\ dBm$ and there are just two interfere signals have intermodulation component at desired signal's frequency, the maximum acceptable power for these signals is $-49\ dBm$ to achieve wanted SINR value [11] [12].

In this simulation, we examine these conditions for GSM receivers and study the impact of IIP3 and power of interfere signals on SINR according to our modified SINR model using tow interfere signals.

A. Impact of IIP3 on SINR

We use the modified SINR model as expressed in Eq. (17) with GSM receiver specifications from [12]. Fig.6 characterizes relationship between third-order input intercept point IP3 and SINR for different interfere signals power P_{e-in} where desired signal at $-99\ dBm$ and noise floor $-111\ dBm$.

The simulation results are: in term to achieve desired SNR value for RF receivers, the IIP3 should increase with increment of the interfere signals power which may produce intermodulation products in the receiver. As given in [11] [12], third-order input intercept point IIP3 for GSM receiver is about $-18\,dBm$. That's mean when desired signal at $-99\,dBm$ and interfere signals with power more than $-49\,dBm$, SINR will fall under accepted value $-9\,dB$.

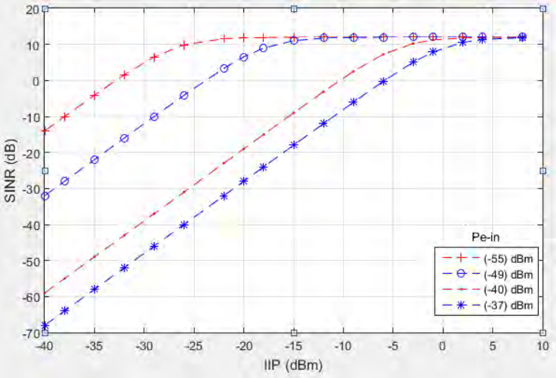

Fig.6. Impact of third-order input intercept point IIP3 on SINR.

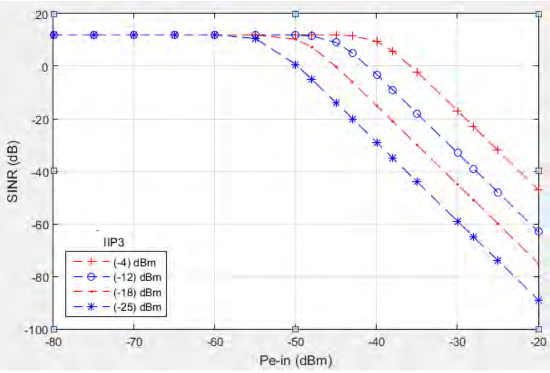

Fig.7. Impact of p_{e-in} on SINR.

B. Impact of interfere signals on SINR

By using our SINR modified model with desired signal at $-99\,dBm$ and noise floor at $-111\,dBm$, relationship between power of interfere signals p_{e-in} and SINR is depicted in Fig.11. To achieve the required SINR for GSM receiver, acceptable interfere signals power is about $-54\,dBm$ when IIP3 is $-25\,dBm$, $-49\,dBm$ when IIP3 is $-18\,dBm$ and about $-40\,dBm$ when IIP3 is $-4\,dBm$. This results show that with increment of the IIP3 value acceptable value for interfere signals power is get increase. From Fig.7, the RF receiver reject for intermodulation products is get higher when IIP3 increase and the linearity of the receiver is increase.

VI. Conclusion

As a result of growth of wireless systems and the existence of many service providers at same area, the intermodulation products distortion rise up as significant issue which should be mitigated to insure required SINR for receivers.

In this paper, we study the effect of third-order intermodulation product on signal-to-interference-and-noise ratio. the results show that when IIP3 increases, the receiver could handle with higher power of interfere signals (producers of third-order intermodulation product) with acceptable value of SINR. Modified SINR model could be used to get control on receiver nonlinearity effect, on the other hand it could be used to modify mobile networks planning technique and frequency allocation algorithms to avoid generating these unwanted interference signals beside of receiver nonlinearity. Thus, there are a lot of challenges for RF receivers designers to achieve all of these requirements.

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