Bit Error Rate Performance of Wireless Communication Systems with Passive Intermodulation Interference

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Abstract. The development of wireless communication systems tends to be high-power, multi-carrier and broadband, which makes the problem of passive intermodulation (PIM) interference in the communication systems more and more serious. When PIM interference falls into the receiving passband of communication systems, the receiving sensitivity of receivers will be reduced and the performance of the receiver will be affected. In this paper, a model is established to analyze the influence of PIM interference on the demodulation link in two cases. One is the constant signal-to-interference ratio (SIR), and the center frequency of PIM interference is the same as the carrier frequency of the uplink received signal, the other is time-varying SIR. Due to numerical simulations, the analysis curve and simulation curve of the bit error rate is basically consistent with each other, indicating that the analysis model is reasonable.

Keywords: passive intermodulation interference · bit error rate · demodulation link · signal-to-interference ratio

1 Introduction

PIM is the phenomenon of interference caused by intermodulation signals generated when two or more transmit carriers are input to fall into the receive passband in a high-power multichannel communication system [1]. Various passive components in the transmitting system have a certain degree of nonlinear characteristics, and in high-power, multi-channel systems, the nonlinearity of these passive components will generate harmonics of a higher order than the operating frequency, and the mixing of harmonics with the operating frequency will generate a new set of frequencies, which will eventually generate a set of interference spectrum in the air and affect normal communication.

In the transceiver communication system, the transmitted signal and the received signal pass through the transceiver duplexer, high-power cable, antenna feed source at the same time. If the PIM products generated between different carriers of the transmitted signal fall into the receive band, the PIM products will enter the receiver together with the received signals at the same time, forming an interference signal. This problem cannot

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be solved by using traditional filter and isolation methods. When the PIM level is low, the bottom noise of the received signal will be raised, so that the receiver signal-to-noise ratio (SNR) decreases and the bit error rate increases; when the PIM level increases further, it will affect the normal operation of the entire communication system, and in serious cases, the PIM will flood the received signal, resulting in channel blockage and communication interruption, which will paralyze the entire communication system.

The impact of passive intermodulation interference on the communication system is mainly reflected in the following two links, namely the demodulation link and the synchronization capture link. Among them, PIM interference affects the demodulation link of the communication system means that when PIM interference is superimposed on the uplink received signal, it will deteriorate the Error Vector Magnitude (EVM) of the uplink received signal so that the verdict of the uplink received signal will be affected and the error code elements will appear in the uplink signal transmission, and then affect the demodulation performance of the uplink communication link. For the impact of PIM interference on the demodulation link of the communication system, the BER of the uplink transmission is used to measure.

The intermodulation phenomenon generated by nonlinear devices in the process of signal transmission has been an important research problem, especially with the development of communication systems towards high-power and multi-carrier, scholars all over the world pay more attention to the research of intermodulation. However, among the many studies of PIM, most of them focus on the analysis of the mechanism of PIM and microwave devices. There are fewer studies on the impact of PIM on the communication system, and the analysis of the influence of more general multi-carrier PIM on system performance needs to be improved. There is little analysis has been done on the statistical properties of PIM and its effects on the system such as bit error rate (BER) performance [2–5]. However, the existing results have focused on analyzing the impact of dual-carrier PIM on the bit error rate of the communication system, and have not analyzed the impact of multi-carrier PIM, which is more common in the actual situation. At the same time, in the existing analysis, the assumption of PIM interference signal is too ideal to achieve an accurate prediction of the influence of PIM on the performance of the communication system.

In this paper, the impact of PIM interference on the demodulation performance of the communication system will be analyzed according to the statistical signal processing theory in combination with the characteristics of PIM interference. In the following analysis model of the effect of PIM interference on the demodulation performance of communication system, the analysis of the effect of PIM interference on the demodulation link under constant SIR, and the analysis of the effect of PIM interference on the demodulation link under time-varying SIR are separately described according to whether the SIR is constant or not.

The rest of this paper is organized as follows. In Sect. 2, the influence of PIM interference on the demodulation link is analyzed when the SIR is constant and the center frequency of PIM interference happens to fall on the carrier frequency of the uplink received signal. In Sect. 3, the influence of PIM interference on the demodulation process is analyzed in the case of time-varying SIR, followed by a brief conclusion in Sect. 4.

2 Bit Error Rate Performance of PIM Interference with Constant SIR

Since any memoryless nonlinear behavior can be described by the power series model, the power series model is used to analyze the influence of PIM interference on demodulation.

$$Y(t) = a_1X(t) + a_2X^2(t) + a_3X^3(t) + \cdots + a_nX^n(t) + \tag{1}$$

where $Y(t)$ is the PIM interference signal; $X(t)$ is the downlink m-way carrier signal, which can be expressed as

$$X(t) = \sum_{i=1}^{m} R_i(t)\cos(2\pi f_i t) \tag{2}$$

where f_i is the frequency of the downlink carrier signal; $R_i(t)$ is the baseband shaping signal with downlink frequency f_i.

Due to the design characteristics of the upstream and downstream signal bands, only the PIM products in the region I (i.e., PIM products with PIM frequencies lower than the second harmonic frequency) are usually considered, so only the PIM interference generated by odd powers of $X(t)$ is considered.

Since the PIM product grows nonlinearly with the number of downlink carriers, only the PIM product of the downlink with dual-carrier and BPSK modulation is considered next. The PIM products of the downlink signal with multi-carrier and other modulation modes can also be analyzed using this method, but it is more complicated.

The downlink $X(t)$ can be expressed as

$$X(t) = \sum_{i=1}^{2} R_i(t)\cos(2\pi f_i t) \tag{3}$$

Then the n ($n = 2p + 1, p$ is a positive integer) order PIM product that falls into the receive band can be expressed as

$$Y_n(t) = R_1^{p+1}R_2^{p}\cos(2\pi((p+1)f_1 - pf_2)) \tag{4}$$

When the baseband signal is modulated using rectangular pulse BPSK (binary phase shift keying), $R_1 = \pm 1$ and$R_2 = \pm 1$, so $R_1^{p+1}R_2^{p}\cos(2\pi((p+1)f_1 - pf_2))$. If R_1 and R_2 take the value of ±1 with equal probability, then the values of $R_1^{p+1}R_2^{p}$ are also taken with equal probability.

When the uplink signal frequency $f_{up} = (p+1)f_1 - pf_2$, then the PIM interference has the greatest impact on the reception of the uplink signal. The PIM interference signal after down-conversion to get the baseband signal can be expressed as

$$Y_b(t) = R_1^{p+1}R_2^{p} = \pm 1 \tag{5}$$

At the uplink signal receiving end, the signal entering the adjudicator can be expressed as

$$z = \sqrt{P_s}X + \sqrt{P_I}Y_b + n \tag{6}$$

where X is the uplink signal per unit energy; Y_b is the interference signal per unit energy; n is the additive Gaussian white noise; P_S is the signal power; P_I is the interference power.

The BER is calculated for $Y_b = +1$ and $Y_b = -1$, respectively. The BER can be expressed as

$$\begin{aligned}
&P_e = P(Y_b = +1)PX = +1P(z\langle 0|Y_b = +1, X = +1) \\
&+P(Y_b = -1)PX = +1P(z\langle 0|Y_b = -1, X = +1) \\
&+P(Y_b = +1)PX = -1P(z > 0|Y_b = +1, X = -1) \\
&+P(Y_b = -1)PX = -1P(z > 0|Y_b = -1, X = -1)
\end{aligned} \tag{7}$$

When $X = \pm 1$ with equal probability and $Y_b = \pm 1$ with equal probability (In the BPSK system), Eq. (7) can be expressed as

$$\begin{aligned}
P_e = {} & \frac{1}{4}P(z\langle 0|Y_b = +1, X = +1) + \frac{1}{4}P(z\langle 0|Y_b = -1, X = +1) \\
&+\frac{1}{4}P(z > 0|Y_b = +1, X = -1) + \frac{1}{4}P(z > 0|Y_b = -1, X = -1)
\end{aligned} \tag{8}$$

The statistical distribution of the signals entering the adjudicator is considered below. Four probability density functions for the conditions $X = \pm 1$ and $Y_b = \pm 1$ can be written as

$$f_{X=+1,Y_b=+1}(z) = \frac{1}{\sqrt{2\pi}\sigma}exp\left(-\frac{\left(z - \left(\sqrt{P_S} + \sqrt{P_I}\right)\right)^2}{2\sigma^2}\right) \tag{9}$$

$$f_{X=+1,Y_b=-1}(z) = \frac{1}{\sqrt{2\pi}\sigma}exp\left(-\frac{\left(z-\left(\sqrt{P_S}-\sqrt{P_I}\right)\right)^2}{2\sigma^2}\right) \tag{10}$$

$$f_{X=-1,Y_b=-1}(z) = \frac{1}{\sqrt{2\pi}\sigma}exp\left(-\frac{\left(z-\left(-\sqrt{P_S}+\sqrt{P_I}\right)\right)^2}{2\sigma^2}\right) \tag{11}$$

$$f_{X=-1,Y_b=-1}(z) = \frac{1}{\sqrt{2\pi}\sigma}exp\left(-\frac{\left(z-\left(-\sqrt{P_S}-\sqrt{P_I}\right)\right)^2}{2\sigma^2}\right) \tag{12}$$

Substituting Eqs. (9) to (12) into Eq. (8), the uplink received BER of the system can be expressed as

$$\begin{aligned}
P_e = {} & \frac{1}{4}\int_{-\infty}^{0} f_{X=+1,Y_b=+1}(z)dz + \frac{1}{4}\int_{-\infty}^{0} f_{X=+1,Y_b=-1}(z)dz \\
&+ \frac{1}{4}\int_{-\infty}^{0} f_{X=-1,Y_b=+1}(z)dz + \frac{1}{4}\int_{-\infty}^{0} f_{X=-1,Y_b=-1}(z)dz
\end{aligned} \tag{13}$$

By simplifying Eq. (13), it can be expressed as

$$\begin{aligned}
P_e = {} & \frac{1}{2}\int_{-\infty}^{0} f_{X=+1,Y_b=+1}(z)dz + \frac{1}{2}\int_{-\infty}^{0} f_{X=+1,Y_b=-1}(z)dz \\
= {} & \frac{1}{4}erfc\left(\left(1 + \frac{1}{\sqrt{SIR}}\right)\sqrt{SIR}\right) + \frac{1}{4}erfc\left(\left(1 - \frac{1}{\sqrt{SIR}}\right)\sqrt{SIR}\right)
\end{aligned} \tag{14}$$

where SIR is the signal-to-interference ratio, $SIR = P_S/P_I$, P_S is the signal power; SNR is signal to noise ratio, $SNR = P_S/N_0$, N_0 is the noise power, $N_0 = 2\sigma^2$.

The analysis and simulation curves of BER with SIR for uplink communication receivers under SNR = 0 dB and SNR = 5 dB are given in Fig. 1.

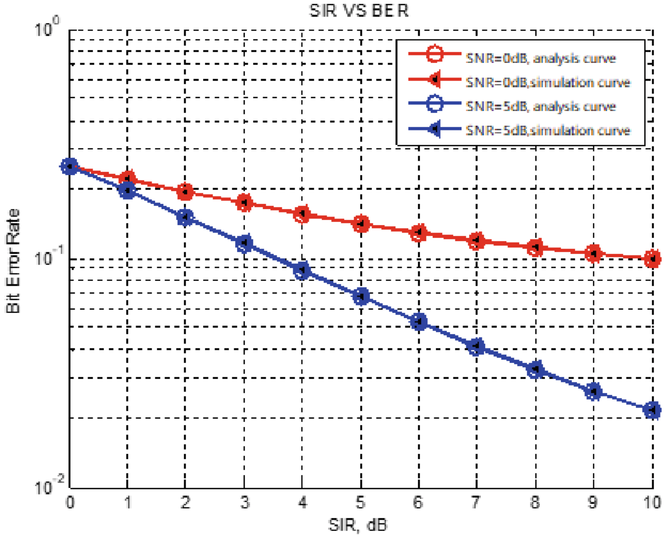

Fig. 1. Analysis and Simulation Curves of BER vs Signal-to-interference Ratio at Constant SNR

From Fig. 1, it can be seen that the analytical curve of the BER variation with the SIR is consistent with the general trend of the simulation curve. The simulation curve basically matches the analysis curve, which indicates that the analysis model is basically reasonable.

The above analysis is based on the assumption that the PIM interference power is constant, the center frequency of the PIM interference is exactly equal to the center frequency of the uplink received signal and the phase of the PIM interference is consistent with the phase of the uplink received signal. The impact of PIM interference on the uplink received signal is the largest, i.e., the above analysis gives the worst performance of the uplink received signal demodulation performance with constant SIR.

3 Bit Error Rate Performance of PIM Interference with Time-Varying SIR

The previous section focused on the effect of PIM interference on the demodulation link at constant SIR, but PIM interference is time-varying and with a constantly changing SIR. This section will focus on the analysis of the impact of PIM interference on the demodulation link at the time-varying SIR. The general idea is to analyze the statistical characteristics of the time-varying SIR, and then find out the variation of the average BER with the average SIR for that period.

The uplink received power of the Rice channel includes the power of the direct signal and the power of the non-direct fading signal, and the uplink received power of the Rayleigh channel has only the power of the non-direct fading signal. Since the power of the direct signal is basically constant, the time-varying part of the received power of both the Rice and Rayleigh channels is the power of the non-direct fading signal. It is easy to see that, in the analysis of time-varying signals, the Rayleigh channel analysis is the basis of the Rice channel analysis, and the two research methods are basically the same, but it is also necessary to analyze the impact of PIM interference on the demodulation link of the communication receiver under the Rice channel.

In the Rayleigh channel, when the signal passes through the channel, its signal amplitude is random and its envelope obeys the Rayleigh distribution. The received power of the uplink receiver is constantly changing.

Represent the signal entering the adjudicator as

$$\mathrm{Z} = \sqrt{\mathrm{P_S}}\mathrm{h_0 x} + \sqrt{\mathrm{P_I}}\mathrm{h_1 y} + \mathrm{n} \tag{15}$$

where x is uplink received signal per unit energy; y is interference signal per unit energy; n is AWGN(Additive White Gaussian Noise); P_S is average power of uplink received signal; P_I is average power of PIM interference; h_0 and h_1 are attenuation coefficients of the changing uplink received signal and PIM interference. In the following analysis, it is assumed that h_0 and h_1 obey Rayleigh distribution.

After entering the judgment, the SINR (Signal to Interference plus Noise Ratio) can be expressed as

$$SINR = \frac{X}{Y + \sigma^2} \tag{16}$$

where $X = |h_0|^2 P_S$, $Y = |h_1|^2 P_I$, X and Y obey exponential distribution. Their probability density functions are denoted as

$$f_X(X) = \frac{1}{P_S} exp\left(-\frac{X}{P_S}\right) \tag{17}$$

$$f_Y(Y) = \frac{1}{P_I} exp\left(-\frac{Y}{P_I}\right) \tag{18}$$

The statistical properties of the SINR are discussed below. The cumulative distribution function of the SINR can be expressed as

$$F_{SINR}(\gamma) = Pr(SINR \le \gamma) = \int_0^{+\infty} Pr\left(X \le \gamma\left(Y + \sigma^2\right)\right) f_Y(Y)dY \tag{19}$$

Substituting Eq. (17) and Eq. (18) into Eq. (19), Eq. (19) can be simplified as

$$F_{SINR}(\gamma) = 1 - \frac{P_S}{P_S + \gamma P_I} exp\left(-\frac{\gamma\sigma^2}{P_S}\right) \tag{20}$$

In the case of time-varying SINR, the effect of PIM interference on the receiver BER can be expressed as

$$SER_L = \int_0^{+\infty} a_{mod} Q\left(\sqrt{2b_{mod}\gamma}\right) f_{SINR}(\gamma)d\gamma \tag{21}$$

where $Q(\cdot)$ is Gaussian Q function; a_{mod} and b_{mod} are parameters related to the modulation mode.

Substituting the Q function into Eq. (21), Eq. (21) can also be expressed as

$$SER_L = \frac{a_{mod}\sqrt{b_{mod}}}{2\sqrt{\pi}} \int_0^{+\infty} \frac{exp(-b_{mod}\gamma)}{\gamma^{1/2}} F_{SINR}(\gamma)d\gamma \tag{22}$$

Under BPSK modulation, $a_{mod} = 1$ and $b_{mod} = 1$. Substituting Eq. (21) into Eq. (22), the relation between BER, average SIR and average SNR under BPSK modulation can be obtained after calculation as

$$P_e = \frac{1}{2} - \frac{1}{2}\sqrt{SIR}{*}exp(SIR(1 + 1/(2SNR)))\Gamma\left(\frac{1}{2}, SIR(1 + 1/(2SNR))\right) \tag{23}$$

where $SIR = P_S/P_I$; $SNR = P_S/N_0$; $N_0 = 2\sigma^2$; and $\Gamma(a, x)$ is defined as follows:

$$\Gamma(a, x) = \int_x^{+\infty} e^{-t}t^{a-1}dt \tag{24}$$

Figure 2 gives the analytical and simulation curves of the BER variation with the average SIR for the uplink with SNR = 5dB and SNR = 25dB under PIM interference.

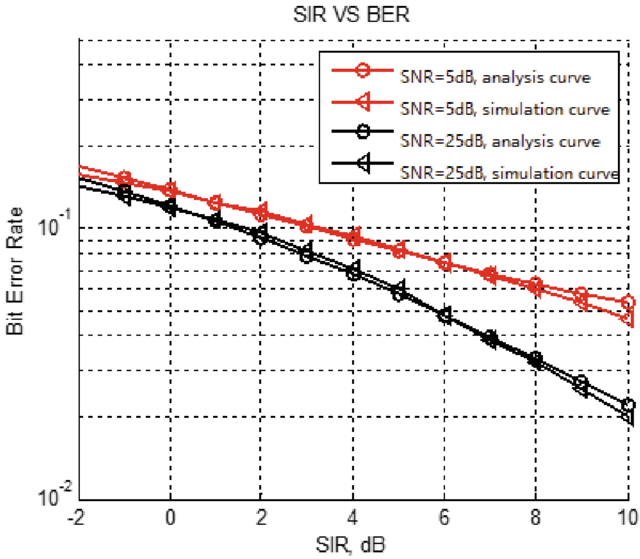

Fig. 2. Analytical and Simulation Curves of BER vs Average SIR at Time-varying SNR

From Fig. 2, it can be seen that the analytical curve of BER variation with SIR is consistent with the general trend of the simulation curve. The error between the simulation curve and the analysis curve is within 2dB, which shows that the analysis of the effect of PIM interference on the demodulation performance of the communication receiver under the time-varying SIR is basically reasonable.

The above analysis is analyzed on basis of that the uplink received power and PIM interference power are subject to an exponential distribution, if the uplink received power and PIM interference power are subject to other statistical characteristics, then the analysis with the above ideas can also get more satisfactory results.

The model of the effect of PIM interference on the demodulation performance of communication receivers under time-varying SIR is more suitable for analyzing the effect of PIM interference on the demodulation performance of communication systems for a long time continuous communication than the model of the effect of PIM interference on the demodulation performance of communication receivers under constant SIR. This is mainly because the communication time of long-time continuous communication is long, and its PIM interference power is constantly changing, and the longer the time, the more its SIR distribution approximately obeys its theoretical SIR statistical characteristics, and the method can be used to analyze the BER of PIM interference on uplink communication link under time-varying SIR.

4 Conclusion

In this paper, the influence of PIM interference on the receiver demodulation performance in the case of constant SIR and the center frequency of PIM interference is the same as the carrier frequency of the uplink received signal, and the SIR is time-varying is analyzed.

(1) The effect analysis of PIM interference on receiver demodulation performance at a constant SIR and the center frequency of PIM interference is the same as the frequency of the uplink carrier and the phase of PIM interference is the same as the phase of the uplink carrier. This is the case where the PIM interference has the greatest impact on the uplink signal at a constant SIR.
(2) When performing the PIM interference analysis under the time-varying SIR, the analysis is performed under the Rayleigh fading channel to consider the time-varying nature of the SIR. The BER of the Rayleigh fading channel is higher than that of the Gaussian channel at the same SIR. That is, the BER of the analytical model under the time-varying SIR is higher when the SIR in the constant SIR analysis is the same as the average SIR in the time-varying SIR analysis.

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