LINEAR RF POWER AMPLIFIER DESIGN FOR WIRELESS SIGNALS: A SPECTRUM ANALYSIS APPROACH

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ABSTRACT

One of the critical and costly components in digital cellular communication systems is the RF power amplifier. Theoretically, one of the main concerns in an RF power amplifier design is the nonlinear effect of the amplifier. Quantitatively, no explicit relationship or expression currently exists between the out-of-band emission level and the nonlinearity description related to the third-order intercept point (IP_3). Further, in experiments and analysis, it was discovered that, in some situations, using IP_3 only is not accurate enough to describe the spectrum regrowth, especially when the fifth-order intercept point (IP_5) is relatively high compared to the third-order intermodulation. In this article, we analyze the nonlinear effect of an RF power amplifier in CDMA (IS-95 Standard), TDMA (IS-54 Standard) and MIRS M-16-QAM (Motorola MIRS standard) system, give an expressions of the estimation of the out-of-band emission levels for each system expressed by power spectrum respectively, in terms of the IP_3 and the IP_5, as well as the power level of the signal. This result will be useful in the design of RF power amplifier for these wireless communication systems.

1. INTRODUCTION

In wireless communication systems, one of the main concerns in RF power amplifier design is the nonlinearity of an RF amplifier can degrade the quality of the transmitted signal, increasing bit error rate and interference to adjacent channels. As a part of the wireless communication standards, such as IS-95 and IS-54, there is special requirement for the control of the nonlinearity of RF amplifiers used in these wireless communication systems [1~3]. The nonlinearity is also called *spectrum regrowth*.

In this article, we analyze the nonlinear effect of an RF power amplifier in the CDMA, TDMA and MIRS M-16-QAM wireless communication systems, developed the expressions of the estimated out-of-band emission levels for each signal respectively, in terms of the power amplifier's intermodulation coefficients IP_3 and fifth-order interception point (IP_5), as well as the power level and bandwidth of the signal. The results presented in this article allow RF Amplifier designers to specify the CDMA, TDMA and MIRS M-16-QAM signal amplifiers using simple IP_3 and IP_5 descriptions. The expressions turn out to be simpler and easier to use for the case where IP_5 may be ignored. In addition, spectrum comparisons between the simulated and predicted results are presented.

2. MODEL DESCRIPTION

Generally speaking, a practical amplifier is only a linear device in its linear region, meaning that the output of the amplifier will not exactly a scaled copy of the input signal when the amplifier works beyond the linear region. Considering an amplifier as a functional box, it can be modeled by a Taylor series [4, 5]. Furthermore, the amplified signal can be described by an equivalent mathematical model as

$$s(t) = r(t)\cdot\cos[2\pi f_c t + \theta(t)] \qquad (1)$$

where $r(t)$ is the baseband envelope of $s(t)$, f_c is the carrier center frequency and $\theta(t)$ is an arbitrary initial phase with a value that does not affect the statistic behavior of $s(t)$. Thus, if the amplitude to phase conversion (AM/PM) is neglected, the output of an amplifier generally can be written as [6]

$$y(t) = O\{s(t)\} = F[r(t)]\cdot\cos(2\pi f_c t + \theta) \qquad (2)$$

where $O\{\cdot\}$ denotes the operation of amplifier, $F[\cdot]$ is the amplitude to amplitude conversion (AM/AM). The functions $F[\cdot]$ and $\Phi[\cdot]$ are dependent on the nonlinearity of the amplifier and modeling type.

Let $\tilde{y}(t) = F[r(t)]$, the Taylor expansion of $O\{s(t)\}$ can be used to determine $\tilde{y}(t)$. Generally, the Taylor model of an RF amplifier can be written as

$$y(t) = \sum_{i=0}^{\infty} a_{2i+1} s^{2i+1}(t)\,. \qquad (3)$$

Here, only the odd-order terms in the Taylor series are considered, since the spectra generated by the even-order terms are at least f_c away from the center of the passband, the effects from these terms on the passband are negligible. Furthermore, as a linear amplifier, only the third- and fifth- order terms dominate in (3) for distortion. Therefore, in this analysis, the following model is used for an RF amplifier:

$$y(t) = a_1 s(t) + a_3 s^3(t) + a_5 s^5(t)\,. \qquad (4)$$

Substituting the input passband signal $s(t) = r(t)\cdot\cos(2\pi f_c t + \theta)$ into $y(t)$ of (4) (after manipulation) produces

$$y(t) = \tilde{y}(t)\cos(2\pi f_c t + \theta) \qquad (5)$$

where

$$\tilde{y}(t) = \tilde{a}_1 r(t) + \tilde{a}_3 r^3(t) + \tilde{a}_5 r^5(t) \qquad (6)$$

with

$$\tilde{a}_1 = a_1,\quad \tilde{a}_3 = \frac{3}{4}a_3,\quad \tilde{a}_5 = \frac{5}{8}a_5\,. \qquad (7)$$

Here, the coefficient a_1 is related to the linear gain G of the amplifier, and the coefficients a_3 and a_5 are directly related to IP_3 and IP_5 respectively. For an amplifier with gain compression $(a_3 < 0)$, it can be proven after a lengthy derivation that the expression for these coefficients becomes

$$a_1 = 10^{\frac{G}{20}},\quad a_3 = -\frac{2}{3}10^{\left(-\frac{IP_3}{10}+\frac{3G}{20}\right)},\quad a_5 = -\frac{2}{5}10^{\left(-\frac{IP_5}{5}+\frac{G}{4}\right)}. \qquad (8)$$

From (5) to (8), it can be seen that an amplifier's output $y(t)$ is a function of G, IP_3, IP_5 and the input signal $s(t)$. Consequently, using (5) and the *Power Spectrum Density (PSD)* of $s(t)$, the PSD of $y(t)$ can be calculated and the power emission levels can be determined. Therefore, all of the nonlinear effects of the amplifier with the wireless communication signals can be evaluated.

Now, the PSD of $y(t)$ can be calculated. Since $y(t) = \tilde{y}(t)\cos(2\pi f_c t + \theta)$, the PSD of $y(t)$ can be determined by the PSD of $\tilde{y}(t)$ as [4]

$$P_y(f) = \frac{1}{4}\left[P_{\tilde{y}}(f - f_c) + P_{\tilde{y}}(f + f_c)\right] \quad (9)$$

and then, the PSD of $\tilde{y}(t)$ can be derived by *Wiener-Khintchine Theorem* as [4]

$$P_{\tilde{y}}(f) = \int_{-\infty}^{\infty} R_{\tilde{y}}(\tau) e^{-j2\pi f\tau}\, d\tau = F\left\{R_{\tilde{y}}(\tau)\right\}. \quad (10)$$

where $F\{\cdot\}$ is the *Fourier transform* of $\{\cdot\}$.

By definition, the correlation function $R_{\tilde{y}}(\tau)$ is expressed as

$$R_{\tilde{y}}(\tau) = E\{\tilde{y}(t) \cdot \tilde{y}(t+\tau)\} \quad (11)$$

where $E\{\cdot\}$ is the *mathematical expectation* of $\{\}$.

Therefore, the PSD of $y(t)$ can be calculated through the autocorrelation function $R_{\tilde{y}}(\tau)$.

3. SPECTRUM ANALYSIS OF RF POWER AMPLIFIER IN CDMA SYSTEM

The CDMA scheme was adopted as a new wireless communication industry standard, IS-95 by the Electronic Industries Association (EIA) and the Telecommunications Industry Association (TIA) in 1933. As part of the IS-95 standard, EIA/TIA has set requirements for the control of the nonlinearity of RF amplifiers used in cellular CDMA systems [1].

The process of deriving $P_y(f)$ is quite tedious [6], but the result turns out to be a closed form, which makes a close examination of $P_y(f)$ possible. $P_y(f)$ can be expressed as

$$P_y(f) = \begin{cases} \frac{1}{2B}\left[P_0 - 6P_0^2 10^{-\frac{IP_3}{10}} - 30P_0^3 10^{-\frac{IP_5}{5}} + 9P_0^3 10^{-\frac{IP_3}{5}} + 90P_0^4 10^{\left(-\frac{IP_3}{10}-\frac{IP_5}{5}\right)} + 225P_0^5 10^{\left(-\frac{2IP_5}{5}\right)}\right] \\ + \frac{1}{8B^3}\left[6P_0^3 10^{-\frac{IP_3}{5}} + 120P_0^4 10^{\left(-\frac{IP_3}{10}-\frac{IP_5}{5}\right)} + 150P_0^5 10^{\left(-\frac{2IP_5}{5}\right)}\right] \cdot \left[3B^2 - (f-f_c)^2\right] \\ + \frac{10}{32}\frac{P_0^5}{B^5} 10^{\left(-\frac{2IP_5}{5}\right)} \cdot \left\{3\left[5B^2 - (f-f_c)^2\right]^2 + 40B^4\right\}, & |f-f_c| \le B \\ \frac{1}{16B^3}\left[6P_0^3 10^{-\frac{IP_3}{5}} + 120P_0^4 10^{\left(-\frac{IP_3}{10}-\frac{IP_5}{5}\right)} + 150P_0^5 10^{\left(-\frac{2IP_5}{5}\right)}\right] \cdot \left(3B - |f-f_c|\right)^2 \\ + \frac{10}{16}\frac{P_0^5}{B^5} 10^{\left(-\frac{2IP_5}{5}\right)} \cdot \left[2B\left(4B - |f-f_c|\right)^3 + 2B^3\left(4B - |f-f_c|\right) - \left(3B - |f-f_c|\right)^4\right], & B < |f-f_c| \le 3B \\ \frac{5}{32}\frac{P_0^5}{B^5} 10^{\left(-\frac{2IP_5}{5}\right)} \cdot \left(5B - |f-f_c|\right)^4, & 3B < |f-f_c| \le 5B \\ 0, & 5B < |f-f_c| \end{cases} \quad (12)$$

where $P_0 = a_1^2 N_0 B/2$ is the linear portion of the amplifier's output power, f_c is the carrier center frequency.

Several observations are made while inspecting (12): in the pass band $|f - f_0| \le B$, the first term $P_0/2B$ corresponds to the linear output power density. The remaining terms in the pass band are caused by the nonlinearity. For a linear amplifier, the cross-modulation power usually is much lower than the final output power. Therefore, the cross modulation does not affect the pass-band spectrum significantly.

There is often a case where the fifth-order intermodulation does not dominate the out-of-band spectrum regrowth. In this situation, (12) may be simplified significantly as [6]

$$P_y(f) = \begin{cases} \frac{1}{2B}\left[P_0 - 6P_0^2 10^{-\frac{IP_3}{10}} + 9P_0^3 10^{-\frac{IP_3}{5}}\right] + \frac{3}{4B^3}P_0^3 10^{-\frac{IP_3}{5}} \cdot \left[3B^2 - (f-f_c)^2\right], & |f-f_c| \le B \\ \frac{3}{8B^3}P_0^3 10^{-\frac{IP_3}{5}} \cdot \left(3B - |f-f_c|\right)^2, & B < |f-f_c| \le 3B \\ 0, & 3B < |f-f_c| \end{cases} \quad (13)$$

This simple result also makes it possible for a designer to estimate the spectrum regrowth when the IP_5 is not available.

With the explicit power spectrum of the output CDMA signal, the out-of-band spurious emission power may be calculated in a particular frequency band. It is this power that is used in IS-95 to specify the limit for the out-of-band emission control. To keep the result easy to use, only IP_3 is considered here.

Let a frequency band be defined by f_1 and f_2 outside the pass band. Using the results from $P_y(f)$, the emission power level within the band (f_1, f_2), denoted as $P_{IM_3}(f_1, f_2)$, can be determined easily by

$$\begin{aligned} P_{IM_3}(f_1, f_2) &= \int_{f_1}^{f_2} P_y(f)\,df \\ &= \frac{1}{8B^3}P_0^3 10^{-\frac{IP_3}{5}}\left[\left(3B - |f_1 - f_c|\right)^3 - \left(3B - |f_2 - f_c|\right)^3\right], \\ & 0 < f_1 < f_2, \quad B < |f_1 - f_c|, \quad |f_2 - f_c| \le 3B \end{aligned} \quad (14)$$

In most design procedures, a designer is concerned with the required IP_3 for a given out-of-band emission level. To obtain the desired IP_3, (14) is solved for and IP_3 with the given $P_{IM_3}(f_1, f_2)$, which yields [6]

$$IP_3 = -5 \cdot \log\left\{\frac{P_{IM_3}(f_1, f_2)B^3}{P_0^3\left[\left(3B - |f_1 - f_c|\right)^3 - \left(3B - |f_2 - f_c|\right)^3\right]}\right\} - 4.52\ dBW \quad (15)$$

This result provides a direct relationship between the out-of-band emission power of a CDMA signal power amplifier and its IP_3. With a given required IP_3, the power amplifier design for a CDMA signal becomes a conventional RF power amplifier design.

For example, the result shown in (15) is used to design an amplifier, which complies with the out-of-band emission level control requirement proposed for CDMA amplifiers. The signal output power from this amplifier is 24.5 dBm. From (15), we get the required IP_3 as 45 dBm [6]. Without loss of generality, IP_5 can be assumed as 42.5 dBm at the same output power level by a *two-tone test* [7]. In *Fig.1*, the dotted line shows the predicted PSD using both IP_3 and IP_5, the dash line shows the predicted PSD using IP_3 only, and the solid line is the PSD measured from a spectrum analyzer.

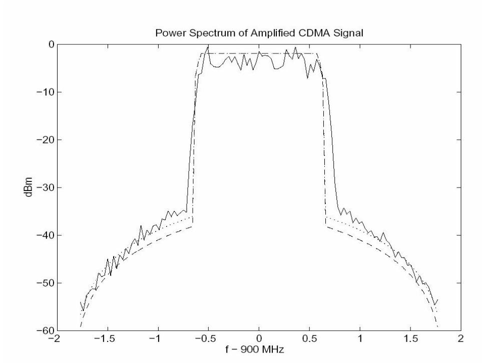

Fig. 1. Predicted output power spectrum for CDMA signals: considering IP_3 and IP_5 vs. IP_3 only

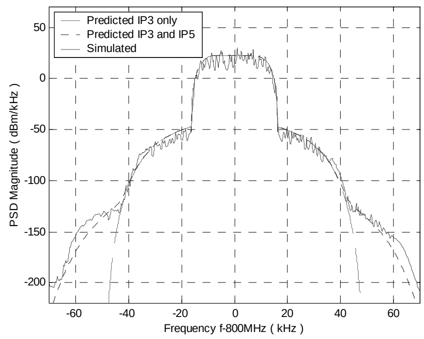

Fig. 2. Predicted output power spectrum for TDMA signals: considering IP_3 and IP_5 vs. IP_3 only

It can be seen clearly that a better fit exists when both IP_3 and IP_5 are used vs. IP_3 only.

4. SPECTRUM ANALYSIS OF RF POWER AMPLIFIER IN TDMA SYSTEM

Time Division Multiple Access (TDMA) is a digital transmission technology that allows a number of users to access a single *radio frequency (RF)* channel without interference by allocating unique time slots to each user within each channel. The TDMA scheme was adopted as a new wireless communication industry standard, IS-54, by the Telecommunications Industry Association (TIA) in 1989 [2].

After a lengthy deviation [8], we can obtain the final result of the power spectrum $P_y(f)$ of $y(t)$ in terms of G, IP_3, IP_5 and P_o:

$$\begin{aligned} P_y(f) = &\frac{P_o}{R_s}\cdot P_1^2(f-f_c) - \frac{2P_o^2}{R_s^2}10^{-\frac{IP_3}{10}}\cdot P_1(f-f_c)\cdot P_3(f-f_c) \\ &-\frac{2P_o^3}{R_s^3}10^{-\frac{IP_5}{5}}\cdot P_1(f-f_c)\cdot P_5(f-f_c) \\ &+\frac{P_o^3}{R_s^3}10^{-\frac{IP_3}{5}}\cdot P_3^2(f-f_c) \\ &+\frac{2P_o^4}{R_s^4}10^{-\frac{IP_3}{10}}\cdot 10^{-\frac{IP_5}{5}}\cdot P_3(f-f_c)\cdot P_5(f-f_c) \\ &+\frac{P_o^5}{R_s^5}10^{-\frac{2IP_5}{5}}\cdot P_5^2(f-f_c). \end{aligned} \tag{16}$$

where f_c is the carrier center frequency, $P_o = a_1^2\cdot P_{in} = a_1^2\cdot A^2R_s^2/2$ is the linear portion of the amplifier output power, in which A is a constant, depending only on the minimum TDMA symbol energy, R_s is the symbol rate, equal to 24.3 kHz for IS-54 standard; $P_1 = |H(f)|$, in which $H(f)$ is the *frequency response* of the baseband filter $h(t)$; $P_3 = P_1\otimes P_1\otimes P_1$, $P_5 = P_1\otimes P_1\otimes P_1\otimes P_1\otimes P_1$, in which $\otimes$ denotes *convolution operator*.

If IP_5 is ignored, (16) will become

$$\begin{aligned} P_y(f) = &\frac{P_o}{R_s}\cdot P_1^2(f-f_c) \\ &-\frac{2P_o^2}{R_s^2}10^{-\frac{IP_3}{10}}\cdot P_1(f-f_c)\cdot P_3(f-f_c) \\ &+\frac{P_o^3}{R_s^3}10^{-\frac{IP_3}{5}}\cdot P_3^2(f-f_c). \end{aligned} \tag{17}$$

Several observations are made by inspecting (17): the first term $(P_o/R_s)\cdot P_1^2$ corresponds to the linear output power density; the remaining terms in (17) are caused by the nonlinearity. In other words, these remaining terms are due to the intermodulation. For a linear amplifier, the intermodulation is usually much lower than the linear output power. Therefore, the intermodulation does not affect the passband spectrum significantly.

As the same method used to get the required IP_3 for CDMA signals, (17) can be used to design a amplifier to meet the power emission requirement in IS-54, which yields [8]

$$IP_3 = -10\cdot\log_{10}\left(\frac{-C_2+\sqrt{C_2^2-4C_1C_3}}{2C_1}\right) \tag{18}$$

where C_1, C_2 and C_3 are described as

$$\begin{aligned} C_1 &= \frac{P_o^3}{R_s^3}\cdot\int_{f_1}^{f_2}P_3^2(f-f_c)df \\ C_2 &= -\frac{2P_o^2}{R_s^2}\cdot\int_{f_1}^{f_2}P_1(f-f_c)\cdot P_3(f-f_c)df \\ C_3 &= \frac{P_o}{R_s}\cdot\int_{f_1}^{f_2}P_1^2(f-f_c)df - P_{IM_3}(f_1, f_2). \end{aligned} \tag{19}$$

in which $P_{IM_3}(f_1, f_2)$ is the emission power level within the band (f_1, f_2). This result provides a direct relationship between the out-of-band emission power of a TDMA signal power amplifier and its IP_3. With a given required IP_3, the power amplifier design for a TDMA signal becomes a conventional RF power amplifier design.

For example, the result shown in (18) is used to design a $4W$ amplifier, which complies with the out-of-band emission level control requirement proposed for TDMA amplifiers. Then, from (18), the required IP_3 becomes $IP_3 = 48.6\ dBm$ [8]. Without loss of generality, IP_5 can be assumed as 45 dBm at the same output power level by the two-tone test [7]. The predicted result using only IP_3 vs. both IP_3 and IP_5 is shown in *Fig. 2*. It can be seen clearly that a better fit exits when both IP_3 and IP_5 are used vs. IP_3 only.

5. SPECTRUM ANALYSIS OF RF POWER AMPLIFIER IN MIRS M-16-QAM SYSTEM

In the early 1990s, Motorola have formed an *Extended Specialized Mobile Radio (ESMR)* service network in the 800/1500 MHz band that could provide capacity and services similar to cellular. Using *Motorola's*

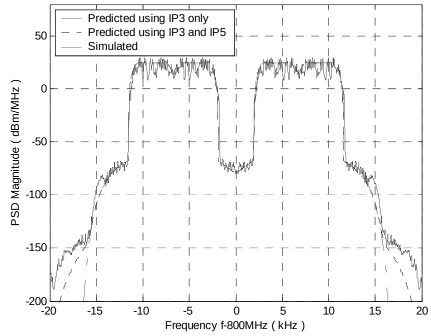

Fig. 3. Predicted output power spectrum for MIRS M-16-QAM signals: considering IP_3 and IP_5 vs. IP_3 only

Integrated Radio System (MIRS), ESMR integrates voice dispatch, cellular phone service, messaging, and data transmission capabilities on the same network [3]. A key feature of this system is using a special modulation method, *16-Quadrature Amplitude Modulation (16-QAM)*. As the same method shown before, we can obtain the final result of the power spectrum $P_y(f)$ of $y(t)$ in terms of G, IP_3, IP_5 and P_o [9]:

$$\begin{aligned} P(f) = & \frac{P_o}{4R_s} P_1^2\left(f-\hat{f}_c\right) - \frac{P_o^2}{8R_s^2} 10^{-\frac{IP_3}{10}} \cdot P_1\left(f-\hat{f}_c\right) \cdot P_3\left(f-\hat{f}_c\right) \\ & - \frac{P_o^3}{32R_s^3} 10^{-\frac{IP_5}{5}} \cdot P_1\left(f-\hat{f}_c\right) \cdot P_5\left(f-\hat{f}_c\right) + \frac{P_o^3}{64R_s^3} 10^{-\frac{IP_3}{5}} \cdot P_3^2\left(f-\hat{f}_c\right) \\ & + \frac{P_o^4}{128R_s^4} 10^{-\frac{IP_3}{10}} \cdot 10^{-\frac{IP_5}{5}} \cdot P_3\left(f-\hat{f}_c\right) \cdot P_5\left(f-\hat{f}_c\right) \\ & + \frac{P_o^5}{1024R_s^5} 10^{-\frac{2IP_5}{5}} \cdot P_5^2\left(f-\hat{f}_c\right) \end{aligned} \tag{20}$$

where $\hat{f}_c$ is the carrier frequency f_c after shifting down 6.75 kHz, $P_o = a_1^2 \cdot P_{in} = 2a_1^2 \cdot E_Q R_s^2$ is the linear portion of the amplifier output power, in which E_Q is a constant, depending only on the minimum 16-QAM symbol energy, R_s is the symbol rate; $P_1 = \frac{1}{2}\sum_{k=0}^{3}\left[\left|H(f-k\Delta f)\right| + \left|H(-f-k\Delta f)\right|\right]$, in which $H(f)$ is the frequency response of transmit pulse shaped filter $h(t)$, Δf is the subchannel frequency spacing, chosen as 4.5 kHz in MIRS standard; $P_3 = P_1 \otimes P_1 \otimes P_1$, $P_5 = P_1 \otimes P_1 \otimes P_1 \otimes P_1 \otimes P_1$, in which $\otimes$ denotes *convolution operator*.

If IP_5 is ignored, (20) will become

$$\begin{aligned} P_y(f) = & \frac{P_o}{4R_s} \cdot P_1^2\left(f-\hat{f}_c\right) - \frac{P_o^2}{8R_s^2} 10^{-\frac{IP_3}{10}} \cdot P_1\left(f-\hat{f}_c\right) \cdot P_3\left(f-\hat{f}_c\right) \\ & + \frac{P_o^3}{64R_s^3} 10^{-\frac{IP_3}{5}} \cdot P_3^2\left(f-\hat{f}_c\right). \end{aligned} \tag{21}$$

Same observations can be made by inspecting (21): the first term $(P_o/4R_s) \cdot P_1^2\left(f-\hat{f}_c\right)$ corresponds to the linear output power density; and the remaining terms in (21) are caused by the nonlinearity, which is caused by the intermodulation. As the same method used above, (21) can be used to design a amplifier to meet the power emission requirement in MIRS standard, which yields [9]

$$IP_3 = -10 \cdot \log_{10}\left(\frac{-C_2 + \sqrt{C_2^2 - 4C_1C_3}}{2C_1}\right) \tag{22}$$

where C_1, C_2 and C_3 are described as

$$\begin{aligned} C_1 &= \frac{P_o^3}{64R_s^3} \cdot \int_{f_1}^{f_2} P_3^2\left(f-\hat{f}_c\right) df \\ C_2 &= -\frac{P_o^2}{8R_s^2} \cdot \int_{f_1}^{f_2} P_1\left(f-\hat{f}_c\right) \cdot P_3\left(f-\hat{f}_c\right) df \\ C_3 &= \frac{P_o}{4R_s} \cdot \int_{f_1}^{f_2} P_1^2\left(f-\hat{f}_c\right) df - P_{IM_3}\left(f_1, f_2\right). \end{aligned} \tag{23}$$

in which $P_{IM_3}(f_1, f_2)$ is the emission power level within the band (f_1, f_2). This result provides a direct relationship between the out-of-band emission power of an MIRS M-16-QAM signal power amplifier and its IP_3. For example, the result shown in (22) is used to design a 5 W amplifier, which complies with the out-of-band emission level control requirement proposed for MIRS standard amplifiers. Then from (22), the required IP_3 becomes $IP_3 = 52.3\,dBm$ [9], and without loss of generality, IP_5 can be assumed as 45 dBm at the same output power level [9]. The predicted result using only IP_3 vs. both IP_3 and IP_5 is shown in *Fig. 3*. It can be seen clearly that a better fit exits when both IP_3 and IP_5 are used vs. IP_3 only.

6. CONCLUSION

It was assumed traditionally that the effects of the fifth- or higher order intermodulation could be ignored. However, if the fifth-order intermodulation is relatively high compared the third-order intermodulation, the out-of-band emission power levels caused by fifth-order intermodulation could be significant.

In this article, we propose the theoretical methods to predict the output power spectrum of the RF power amplifier in CDMA, TDMA and MIRS M-16-QAM systems so that the traditional nonlinearity parameter IP_3 and additional parameter IP_5 are linked directly with out-of-band emission levels. This analysis makes it possible for RF power amplifier designers to use a conventional approach to design RF power amplifiers for CDMA, TDMA and MIRS M-16-QAM signals. In addition to the results presented in this article, this derivation approach can be applied to out-of-band emission level analysis for other communication standards.

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