Study on Evaluation Method for Nonlinear Characteristics of Wireless Communication System - Spurious Domain Emissions of 256-QAM and OFDM Waves -
Masayoshi Tanaka*

1 Introduction
High-speed wireless communications use multi-carrier or multi-level modulated waves with large amplitude variations such as OFDM (Orthogonal Frequency Division Multiplexing) or 256-QAM (Quadrature Amplitude Modulation). These are sensitive to nonlinearities. Nonlinear operation of high power amplifier (HPA) not only degrades communication performance, but also generates unwanted waves (spurious) outside the necessary band. In order to meet acceptable spurious levels, operation in the linear region with the output back-off of HPA results in a decrease in power efficiency, resulting in an increase in power consumption.

To clarify the optimal operating point of HPA for building an energy-saving economical system, the spurious level must be accurately estimated from the HPA nonlinearity AM-AM (Amplitude Modulation-Amplitude Modulation) and AM-PM (Amplitude Modulation-Phase Modulation) conversions.

In this paper, we propose a method to analyze spurious characteristics by calculating AM-AM and AM-PM conversions from only measured amplitude information. Based on this method, we examined the validity of the estimation of spurious domain emissions generated when a 256-QAM or OFDM signal was transmitted.

2 Nonlinear characteristics
2.1 Outline
As shown in Fig. 1 (a), AM-AM conversion shows the change in output power (Pout) with respect to the change in input power (Pin). If this change is not linear, nonlinear distortion occurs in the output signal. On the other hand, as shown in Fig. 1 (b), AM-PM conversion shows the phase change ϕ between input and output with respect to Pin. If the phase changes when Pin increases, phase rotation and transmission distortion will occur.

2.2 Influence of nonlinear characteristics
Figure 2 shows the relationship between a typical HPA operating point and power efficiency. As input power increases and approaches the saturation region, nonlinearity degrades transmission characteristics and generates unwanted waves outside the required band. However, HPA power efficiency improves and low power consumption can be expected. Figure 3 shows the generation of unwanted emissions. In particular, compliance with acceptable levels of spurious domain is specified (1-3). Where Bn is the occupied frequency bandwidth during communication.

Fig. 1 AM-AM (a) and AM-PM (b) conversions.

Fig. 2 HPA power efficiency versus driving point.

2.3 Issue of phase nonlinearity measurement
AM-PM conversion characteristics can be obtained by directly measuring the phase difference between input and output with a phase meter or a network analyzer. However, the measurement system is complex and expensive. In addition, in relay systems with different input and output frequencies, this method cannot measure the phase difference.

3 Principle of two-tone method
When two waves (F1 and F2) of different levels are applied to a nonlinear element, intermodulation distortion (F3) occurs at the output, as shown in Fig. 4. In this case, the input voltage Vin and output voltage Vout can be described by Eqs. (1) and (2). Where Pin = Vin² and Pout = Vout².

*: Dept. of Electrical and Electronic Eng., College of Industrial Technology, Nihon Univ.
1-2-1, Izumicho, Narashino, Chiba, 275-8575, Japan
This study therefore uses a polynomial approximation consisting of a number of parameters.

4.2 Validation process of analytical method

Figure 5 shows the validation process of the analytical method. The procedure is shown below.
(a) Measure A1, B1, A2, B2, and C2 of the device under test (DUT) when the level difference $\Delta A$ between the two waves 20, 25, and 30 dB.
(b) Using Eq. (4), calculate the phase change value $k_p$.
(c) Integrate the phase change value to obtain the phase $\phi$.
(d) Create polynomial approximation models of amplitude and phase characteristics by fifth, seventh, and ninth order polynomials using the least squares fitting to the DUT data.
(e) Estimate spurious characteristics using the above models.
(f) Compare the characteristics obtained in (e) with those of the reference model as shown in Eqs. (5) and (6) shown later.

4.3 Reference model for approximate model validation

In order to investigate the validity of this analytical method, the reference model was set in place of an actual device as follows. The relationship between $V_{in}$ and $V_{out}$ is defined as Eq. (5) and the phase $\phi$ as Eq. (6) (5).

$$V_{out}(V_{in}) = \frac{2.1587 \cdot V_{in}}{1 + 1.1517 \cdot V_{in}^2}$$  
(5)

$$\phi(V_{in}) = \frac{4.0033 \cdot V_{in}}{1 + 9.104 \cdot V_{in}^2}$$  
(6)
5 Validation of analytical method

The characteristics were estimated by varying the order of the polynomial approximation and the level difference $\Delta A$. As input signals, 256-QAM and OFDM waves were used, since they have large amplitude fluctuations and are sensitive to nonlinearities.

5.1 Approximated HPA characteristics

Figure 6 shows HPA input/output characteristics and phase characteristics approximated by fifth, seventh, and ninth order polynomials ($\Delta A = 30$ dB). Those of the reference model are displayed together. All approximate models closely reproduce the reference characteristics.

Figure 7 shows the approximate HPA and reference characteristics when the level difference $\Delta A$ is changed to 20, 25, and 30 dB with the ninth order model. The approximate characteristics reproduce the reference characteristics well, except for the phase characteristics near the output saturation region.

5.2 Spurious characteristics of 256-QAM

A 256-QAM wave with a PAPR (peak-to-average power ratio) of approximately 6 dB was applied to the approximate models and the output spectra were observed.

Figure 8 compares the spectra analyzed using fifth, seventh, and ninth order polynomials ($\Delta A = 30$ dB) with the spectrum of the reference model. These are the characteristics at the point where the HPA output is 3 dB backed off from saturation. The approximated models accurately reproduced the reference characteristics including the out-of-band output.

Figure 9 shows the spectra when $\Delta A$ was changed to 20 dB, 25 dB, and 30 dB with the ninth order model and the HPA output was 3 dB back from saturation. These spectra accurately reproduce the reference spectrum regardless of $\Delta A$.

5.3 Spurious characteristics of OFDM

Next, the output spectra of OFDM wave with amplitude fluctuations exceeding 256-QAM were observed. The number of OFDM carriers is 2048, and the PAPR is about 10 dB.

Figure 10 shows the spectra at HPA 10 dB output back-off from saturation ($\Delta A = 30$ dB) for the fifth, seventh, and ninth order analytical models. The levels of the spurious domain region using the 5th and 7th order fitting models have a large error compared to those of the reference model. Therefore, a ninth-order model is required for analysis in the region of 2.5 Bn or more from the center frequency. This result is in good agreement with the relationship between...
measured data and estimated data for non-OFDM multicarrier waves (8,9).

Figure 10 shows the spectra at the 10dB output back-off of HPA. (5th, 7th, & 9th order, ΔA = 30 dB).

5.4 Discussion of analytical method

From the above results, it can be seen that as for the level difference ΔA at the time of measurement, the phase accuracy of the 20 dB model slightly decreases near the saturation region of HPA, but has little effect on the spurious levels of 256-QAM and OFDM.

The 256-QAM spectra are less affected by the degree of polynomial approximation. On the other hand, a ninth-order model can accurately estimate the spurious domain emission of OFDM with larger amplitude fluctuations than 256-QAM. Errors are observed for spurious over 3.5 Bn from the center frequency, but the spurious in this region generated in actual systems are below thermal noise and can be ignored (9).

6 Conclusion

In order to estimate the HPA nonlinear characteristics in the spurious domain, we investigated an analytical method using the two-tone method that measures phase change using only amplitude information. The models used for the analysis were created with three level differences of 20, 25, and 30 dB between the two waves and polynomial approximations of the fifth, seventh, and ninth orders. Applying 256-QAM and OFDM waves as input signals to the models, the estimated spurious domain emissions were compared to those of the reference model to validate the analysis. The level difference of the two-tone method during measurement has little effect on the spurious level. Ninth order polynomial approximation model can estimate spurious domain emission of the OFDM wave more accurately than fifth or seventh order approximation.

From the above study, it became clear that spurious domain emissions can be estimated with high accuracy using the easy and economical two-tone method and ninth order polynomials.

References

[1] Spurious emissions, Recommendation ITU-R SM. 329-9,
[3] Tables of maximum permitted power levels for spurious or spurious domain emissions, APPEND.