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Non-contact PIM Measurement Method for Antenna using High-level IM Standard

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Abstract—A non-contact passive intermodulation distortion (PIM) measurement method for antenna using high-level IM standard (HIMS) is described as proposed herein. A novel method to estimate coupling loss between sensing antenna and a sample antenna is proposed, after which a complete one-port non-contact measurement for antenna is realized. Measurements are conducted in three stages: measuring IM characteristics of HIMS, estimating coupling loss using HIMS, and estimating practical PIM level of a sample antenna. A high-level IM standard consisting of a Schottky barrier diode was used for this study. The method enables ready evaluation of practical PIM of a sample antenna from a complete one-port non-contact measurement with excellent stability and repeatability. Then the validity of the proposed method was confirmed experimentally using a printed dipole antenna. After presenting an applicable measurement method for array antenna incorporating the proposed method, its effectiveness was verified experimentally.

Index Terms—antenna measurement, non-contact measurement, nonlinear noise, passive intermodulation

I. INTRODUCTION

Intermodulation distortion (IM) is a spurious wave produced when multiple frequencies are applied to a nonlinear device, in which one caused by residual nonlinearity in passive linear devices is designated as passive intermodulation distortion (PIM). Actually, PIM is much weaker than IMs of nonlinear devices. However, PIM often presents severe difficulties in base station antennas of mobile communication systems because it is not negligible in comparison with weak uplink signals [1]–[5]. Investigations of their mechanisms have also been conducted for PIM sources such as printed circuits and for coaxial connectors and waveguide flanges [6]–[11].

Standard documents related to PIM measurements have been published by IEC [12]. As described in them, observed PIM is classified into two types: one is PIM propagating toward the transmitter, which is designated as reverse PIM (R-PIM); the other is propagating to a matched load, which is designated as forward PIM (F-PIM). Now related to a base-station antenna system, R-PIM is fundamentally important because it has possible interference with a weak uplink signal. Therefore, most earlier studies have used methods by which the antenna under test (AUT) is connected directly to a PIM tester for measurement of R-PIM or of R-IM [13]–[16]. As described herein, we designate the method as direct measurement (DM). Fig. 1(a) portrays a diagram of the DM environment.

This basic and simple method can evaluate PIMs of practical antennas that are shared in transmission and reception systems.

In fact, PIM measurement is sensitive to the contact state at metallic junctions, thus several non-contact PIM measurement methods have been proposed [17]–[19]. The methods reported in the literature [17], [18] were applied to large components such as antennas and microstrip lines. However, non-contact measurement was introduced partly for the PIM-detecting probe. A complete one-port non-contact measurement using a coaxial tube was proposed in earlier reports [19]. It had shortcomings in terms of the sample-size limitation because it used a coaxial tube. Therefore, it has been extended to larger samples such as antennas [20], [21]. As described herein, complete non-contact measurements for antennas are denoted as non-contact measurements (NCM). Actually, Fig. 1(b) is a diagram portraying the NCM concept. Using this method, AUT is excited by a sensing antenna connected to a PIM tester. Then the PIM signal re-radiated from the AUT is received by the PIM tester via the sensing antenna.

When using NCM for antenna PIM measurements, two major differences from DM must be considered. One is the component to be observed and evaluated. The other is the existence of the coupling loss between sensing antenna and AUT. The former is that the PIM signal observed physically in NCM is F-PIM radiated into space from AUT, which is not R-PIM in DM. However, DM can be estimated using NCM because the PIM power produced by a PIM source is split equally to the generator side and the termination side when the circuit is under a good matching condition [13]. For the latter, how the loss in practical measurement procedures is measured is important. The direct method is to use vector network analyzers (VNA) [21]. It should be done in practical power, which is much greater than that in popular microwave measurements. It is necessary for high precision measurements. However, that is an expensive process that is not cost-effective.

Based on the background presented above, this paper presents a proposal of a novel method to estimate the coupling loss using a high-level IM standard (HIMS) for non-contact PIM measurements for an antenna. It is beneficial that the proposed method does not need any expensive VNA measurement in practical power to obtain the coupling loss between AUT and sensing antenna. Its validity was confirmed based on this study through PIM measurement of a printed dipole antenna and its two-element array using a HIMS consisting of a diode. It is also valuable to undertake an examination of PIM in array antennas because few reports have described non-contact PIM measurement for array antennas, except for fundamental work

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on PIM localization [22].

The paper is organized as follows. In section 2, the concept of the proposed method is described through a PIM measurement of a printed dipole antenna. Results demonstrating its validity are presented. In section 3, the proposed method is shown through experimentation to be applicable to array antennas using a two-element array of the printed dipole antenna. Finally, this paper is concluded in section 4.

Fig. 1. Diagrams of PIM measurements of two types for the antenna

II. CONCEPT OF NCM USING HIMS

As described in this paper, all experiments were conducted in the 2 GHz band. The transmitting frequencies f_1 and f_2 are, respectively, 2.05 GHz and 2.20 GHz. The observed PIM or IM is the third-order one at $f_{im} = 2f_1 - f_2 = 1.90$ GHz.

Fig. 2 shows block diagrams of the proposed measurement systems. The measurement is conducted in three stages as shown in (a), (b), and (c), which are labeled respectively as the first, second, and third measurements. In the second and third measurements, AUT is coupled to a sensing antenna electromagnetically without direct connection, which implies non-contact measurement.

Fig. 3(a) presents the HIMS configuration used for this study. Because it is necessary to produce a dominant IM signal for the second measurement, it is desirable to have high nonlinear characteristics. A diode mounted in the center of a microstrip line (MSL) is used as HIMS. The dielectric substrate is 1.6 mm thick with relative dielectric constant $\epsilon_r = 2.6$. The line width is adjusted to match 50Ω . The diode used as HIMS for this study is the Schottky barrier diode (RB721Q-40; Rohm Co. Ltd.).

Fig. 3(b) depicts the configuration of PIM-source model used for this study. This model is used in an antenna or feeding circuit. It is tested later in the third measurement as the PIM source in AUT. Because it is necessary to produce a weaker IM signal than that of HIMS, a pair of parallel diodes is mounted in the middle of the MSL. The mounted diode, dielectric substrate, and all parameters are identical to those of HIMS.

Fig. 4 shows transmission and reflection characteristics of HIMS and the PIM-source model. At test frequencies (f_1, f_2, f_{im}) , it was confirmed that both models have low-loss characteristics. In addition, Table I shows the observed

IM level when #a is connected to the PIM tester and when #b is terminated at applying -10 dBm/tonne from the PIM tester. The observed IM level of the PIM-source model is weaker than that of HIMS by 18 dB. Based on that finding, it can be confirmed that the HIMS and PIM-source model are a low-loss transmission line with high-level IM source, low-level PIM source, respectively, at test frequencies of (f_1, f_2, f_{im}) . As described herein, the IM signal generated by the PIM-source model is denoted as PIM, whereas the one generated by HIMS is denoted as IM. Each will be described separately.

In the following, we explain details of each measurement stage with experimentally obtained results obtained using a basic single-element model.

Fig. 2. Block diagrams of measurement systems of the proposed method.

Fig. 3. Configurations of the HIMS and PIM-source model.

Fig. 4. Transmission (Trans.) and reflection (Ref.) characteristics of HIMS and PIM source model.

TABLE I
COMPARISON OF OBSERVED PIM LEVEL OF THE PIM-SOURCE MODEL WITH HIMS AT APPLYING 10 DBM/TONE

Model	PIM level [dBm]
HIMS	-85.3
PIM-source model	-104

A. Basic single-element model

Fig. 5 portrays a configuration of sensing antenna #1 and AUT #2 when a single element printed dipole antenna is used as AUT. The patch antenna on the left side, which is used as sensing antenna, is identical to that used in studies reported in the literature [21]. The printed dipole antenna is also identical to that in the literature [21], [23] except for feeding-line structure, which is fabricated by the same dielectric substrate of HIMS. The MSL on the back side of the substrate couples electromagnetically to the antenna via the notch. The PIM-source model shown in Fig. 3(b) is used on the back side MSL for testing in the third measurement.

Fig. 6 presents reflection characteristics of the sensing antenna and AUT. At test frequencies (f_1, f_2, f_{im}), reflection coefficients are under -10 dB. This finding indicates that antennas are in a good matching condition.

Fig. 5. Configurations of the sensing antenna and AUT with PIM-source model.

Fig. 6. Reflection coefficient of sensing antenna and AUT.

B. First measurement

In the first measurement shown in Fig. 2(a), HIMS is connected directly to the PIM tester to measure its IM characteristics. Specifically, the IM level generated by HIMS $IM_{gen,n}$ [dBm] is measured as a function of applied power $P_{in,n}$ [dBm/tone], where “n” is an integer label denoting the measurement point ($n = 1, 2, \dots$). Then, an increase coefficient C_n [dB/dB], which is denoted as “power slope” in this paper, is given by the next equation.

$$C_n = \frac{IM_{gen,n+1} - IM_{gen,n}}{P_{in,n+1} - P_{in,n}} \quad (1)$$

Fig. 7 portrays a measured IM level $IM_{gen,n}$ (blue line). The power slope C_n (red line) is calculated based on equation (1) using the measured IM level $IM_{gen,n}$. It shows that the power slope C_n fluctuates over $P_{in,n} = -2$ dBm/tone, although it remains at approximately 3 in a small input-power range. For this reason, power slope C_n should be defined as a function of applied power $P_{in,n}$ for calculation in the next second measurement.

Fig. 7. IM characteristics $IM_{gen,n}$ and power slope C_n of HIMS as a function of applied power $P_{in,n}$ in the first measurement.

C. Second measurement

In the second measurement, HIMS is installed on AUT; NCM is performed as shown in Fig. 2(b). In this case, the

sensing antenna #1 in Fig. 5 is connected to the PIM-tester; AUT #2 is connected to a termination via HIMS. The observed IM level IM_{re} is expressed as the following equation on a decibel scale, where $P_{in,j}$ is output from the PIM tester.

$$IM_{re} = IM_{gen,j} - \int_{P_{in,j}-|S_{c,f_1}|}^{P_{in,j}} \frac{2}{3} C_n(P) dP - \int_{P_{in,j}-|S_{c,f_2}|}^{P_{in,j}} \frac{1}{3} C_n(P) dP + S_{c,f_{im}} \quad (2)$$

Therein, coupling losses between the sensing antenna and AUT at f_1, f_2 , and f_{im} are, respectively, S_{c,f_1}, S_{c,f_2} , and $S_{c,f_{im}}$. The first term on the right side $IM_{gen,j}$ is an IM level caused by HIMS when $P_{in,j}$ is applied directly to it. In other words, it is the result of the first measurement when the applied power is $P_{in,j}$. The second and third terms represent the decrease of the generated IM because of the decrease of applied power at the respective transmitting frequencies of f_1, f_2 . As described above, power slope C_n is a function of the applied power. It is calculated by integration over a range to express the total decrease. The fourth term shows the coupling loss that is incurred when the generated IM is received by the sensing antenna. If the transmitted signals f_1, f_2 and the IM signal f_{im} are mutually close, then coupling losses can be approximated as $S_{c,f_1} \approx S_{c,f_2} \approx S_{c,f_{im}}$. This approximation is natural because these test frequencies are in antenna bandwidth. Denoting these losses as S_c , equation (2) enables its solution as a transcendental equation for quantity S_c .

Table II presents the calculated power slope in the first measurement using HIMS. For these discrete samples, equation (2) is discretized as shown below.

$$h(S_c) = IM_{gen,j} - IM_{re} - \sum_{n=i}^{j-1} C_n \Delta P_n + S_c \quad (3)$$

$$\Delta P_n = P_{in,n+1} - P_{in,n}$$

In those equations, “i” is an arbitrary integer label; S_c is expressed as $\sum_{n=i}^{j-1} \Delta P_n = S_c$. The solution of transcendental equation $h(S_c) = 0$ is given as coupling loss S_c . As described above, IM signal observed in this case must be dominated by the one caused by HIMS. For that reason, a sufficiently high-level standard is required as HIMS.

Table III presents comparison of an estimated coupling loss (Est.) based on equation (3) with a measured coupling loss (Meas.) using VNA when the distance between the sensing antenna and AUT is $d = 160, 210, 260$ mm. In this case, output power from PIM tester is $P_{in,j} = 10$ dBm/tonne, and $IM_{gen,j} = -26.5$ dBm is obtained from the result of the first measurement. The observed IM level is $IM_{re} = -90.2, -95.9, -101.7$ dBm, respectively, at $d = 160, 210, 260$ mm. The estimated value (Est.) can be regarded as a value obtained when the frequency characteristics are negligible, whereas the VNA measurements (Meas.) are values including the exact frequency dependency at each frequency. The table shows that the coupling losses are estimated with a difference

of 2.3 dB against the VNA measurements. In the estimation, existence of HIMS affects the radiation pattern of AUT because the gain of AUT is low, which is regarded as a possible cause of the difference. However, detailed discussions are left as a subject for future work.

TABLE II
POWER SLOPE C_n CALCULATED THROUGH THE FIRST MEASUREMENT

Label	$P_{in,n}$	$IM_{gen,n}$	C_n
1	-21 dBm/tonne	-120.1 dBm	3.2
2	-20 dBm/tonne	-116.8 dBm	3.4
...	...	...	...
i	$P_{in,i}$	$IM_{gen,i}$	C_i
...	...	...	...
j	$P_{in,j}$	$IM_{gen,j}$	C_j
...	...	...	...

TABLE III
ESTIMATED COUPLING LOSS (EST.) BASED ON EQUATION (3) AND MEASURED COUPLING LOSS (MEAS.) USING VNA IN THE SECOND MEASUREMENT FOR THE BASIC SINGLE-ELEMENT MODEL SHOWN IN FIG. 5.

Distance d	Est.	Meas.(f_1)	Meas.(f_2)	Meas.(f_{pim})
160 mm	-16.1 dB	-14.6 dB	-16.4 dB	-14.4 dB
210 mm	-17.5 dB	-16.3 dB	-17.9 dB	-15.2 dB
260 mm	-18.9 dB	-17.5 dB	-18.4 dB	-17.5 dB

D. Third measurement

In the third measurement, HIMS is removed from AUT; NCM is performed for only AUT, as shown in Fig. 2(c). In this case, sensing antenna #1 in Fig. 5 is connected to the PIM tester; AUT #2 is terminated. The power applied to AUT P_{AUT} in NCM is expressed as follows in the decibel scale.

$$P_{AUT} = P_{in} + S_c \quad (4)$$

In that equation, P_{in} is the output power from the PIM tester. A generated PIM is also attenuated by the coupling loss. It is received by the sensing antenna. Therefore, the generated PIM level $PIM_{Est.DM}$ is expressed as follows in the decibel scale.

$$PIM_{Est.DM} = PIM_{re} - S_c \quad (5)$$

In that equation, PIM_{re} is a PIM level observed by the PIM tester. In this way, we enable estimation of the DM-value from NCM-value based on equations (4) and (5) using coupling loss S_c , which has already been estimated in the second measurement. This is the main process of compensation from the NCM-value to the DM-value. It is denoted as DM-NCM conversion in this paper.

Fig. 8 shows DM-NCM conversion results for the model shown in Fig. 5. $PIM_{Est.DM}$ is the estimated DM-value by NCM-value through the above process. It is calculated using coupling loss $S_{c,Est.}$ estimated by the second measurement. Because a sensing antenna has excellent low-PIM characteristics, residual noise is always below -130 dBm in this case. The directly measured DM-value is PIM_{DM} , which is found by connecting the PIM tester directly to AUT #2 in Fig. 5. The estimated DM-value $PIM_{Est.DM}$ can be confirmed to agree

with the measured DM-value PIM_{DM} , with maximum error of about 3 dB. As a reference, the result estimated DM-value $PIM'_{Est,DM}$ calculated using the actual coupling loss $S_{C,mea}$ measured by VNA at $d=160$ mm is presented in Fig. 8, which is presented as the dotted line. Because the calculated result based on $S_{C,mea}$ shows good agreement with the measured DM-value PIM_{DM} , we infer that the difference between estimated result $PIM_{Est,DM}$ and measured result PIM_{DM} is attributable to the small estimation error of the coupling loss obtained using HIMS in the second measurement.

Fig. 8. Estimated DM-value $PIM_{Est,DM}$ from NCM using coupling loss $S_{C,Est}$, estimated in the second measurement, and the estimated DM-value $PIM'_{Est,DM}$ using coupling loss $S_{C,Meas}$, measured by VNA and measured DM-value PIM_{DM} in the third measurement for the basic single-element model shown in Fig. 5.

III. APPLICABLE METHOD FOR ARRAY ANTENNA

This section presents the practically applicable method for array antenna applied from the method proposed above. The method proposed in the preceding section is directly applicable to the far-field of array antenna. However, it is not practical from the viewpoint of requiring a large measurement space. Therefore, we consider feeding each antenna element independently with each excitation factor. As shown in Fig. 9, each antenna element is coupled with a small dipole probe in its vicinity. In this case, for the array fed with equal amplitude with phase difference δ , each element is excited by each small dipole probe with a phase delay of δ . In other words, probe #P2, which excites antenna element #E2, is fed with a phase delay of δ compared with probe #P1. Also, L_a, L_s, δ represents the electrical length. To remove the effect of impedance mismatching caused by small dipole probes, a Wilkinson divider is used to feed with equal amplitude and with appropriate phase difference. In this symmetrical excitation method, DM-NCM conversion enables performance using the coupling loss similarly the basic single-element model shown in section 2. Detailed theoretical calculations are attached in Appendix A.

Fig. 10(a) shows model 2A, in which a PIM source is located in antenna element #E2A, which is identical to that

used in Fig. 5, whereas Fig. 10(b) shows model 2B, in which a PIM source shown in Fig. 3(b) is located at the origin of the feeding circuit. Both models are a two-element printed dipole array antenna fed by MSL-feeding-circuit with phase-difference L_δ adjusted to tilt the main beam to a 20 degree direction from the front. The Wilkinson divider comprises the MSL and a chip resistor. The feeding-circuit and Wilkinson divider are fabricated using the same dielectric substrate to HIMS, as shown in section 2. In both models, small dipole probes with length of about $\lambda/3$ are used. Also, an isolation cable (5B-002-18-07-113FBW; Cadox System Inc.) is used to suppress the leakage current. Then, the whole circuit on the left side for detection of PIM for AUT is denoted as a sensing antenna.

Table IV presents results of the estimated coupling loss and the measured one using VNA in the second measurement. In this case, the output power from the PIM tester is $P_{in,j} = 10$ dBm/tonne; the observed IM level is $IM_{re} = -104.8, -104.0$ dBm, respectively, for model 2A and model 2B. The estimated coupling loss shows good agreement with the measured VNA.

Fig. 11 presents results obtained for DM-NCM conversion using the estimated coupling losses in the manner described in section 2. Unlike a basic single-element model, residual noise is caused mainly by sensing antenna, which has a complicated circuit in this case. For that reason, we must evaluate it carefully. It is recommended that residual noise be lower than the actual PIM level by 10 dB [12]. Because this requirement is met in both models, the validity of the observed PIM level is confirmed. It is apparent that the estimated DM-value $PIM_{Est,DM}$ are in good agreement with measured DM-value PIM_{DM} . In the result obtained for model 2B, little difference was found between the slope of $PIM_{Est,DM}$ and PIM_{DM} , which is regarded as a possible cause of the fluctuation of coupling loss S_C , depending on the power range. However, detailed discussion of this matter is left as a subject for future work.

Fig. 9. Configuration for the array antenna measurement method using small dipole probes.

TABLE IV
COMPARISON OF AN ESTIMATED COUPLING LOSS (EST.) BASED ON EQUATION (3) WITH A MEASURED COUPLING LOSS (MEAS.) USING VNA IN THE SECOND MEASUREMENT FOR ARRAY ANTENNA MODELS

Model	Est.	Meas. (f_1)	Meas. (f_2)	Meas. (f_{pim})
Model 2A	-19.7 dB	-19.0 dB	-18.0 dB	-21.3 dB
Model 2B	-19.5 dB	-19.5 dB	-18.2 dB	-21.6 dB

Fig. 10. Configuration of array antenna models.

IV. CONCLUSION

As described in this paper, we proposed a novel method to estimate coupling loss using a high-level IM standard (HIMS) for non-contact PIM measurement for antenna. As a result, the proposed measurement enables estimation of the practical PIM characteristics in a complete one-port non-contact measurement. Its validity is confirmed through PIM measurement of a printed dipole antenna using a HIMS consisting of a diode. In addition, this report presents description of an applicable measurement method for array antenna applied from the proposed method. Specifically, a small dipole probe was used for each element. It was excited with an appropriate phase difference depending on the excitation factor. Experimentally obtained

Fig. 11. Estimated DM-value $PIM_{Est,DM}$ from NCM using coupling loss $S_{C,Est}$, estimated in the second measurement and measured DM-value PIM_{DM} in the third measurement for array antenna models shown in Fig. 10

results show that the observed PIM level enabled similar conversion to practical PIM characteristics as well as for array antenna. Development of an advanced measurement system that is applicable for all array antennas with a complicated feeding-circuit is regarded as a subject to be undertaken for future work.

APPENDIX A

THEORETICAL CALCULATION FOR AN ARRAY ANTENNA MEASUREMENT SYSTEM

In this section, all parameters are calculated on a linear scale unless stated otherwise. Fig. 12 is a modified Fig. 9, where all the ends of the array circuit are labeled as # m ($m = 1 \dots$). A PIM source located at #5 is denoted as PIM-Source-A. One located at #6 is defined as PIM-Source-C. Transmitting powers are delivered from the right side in DM, whereas transmitting powers are delivered from the left side in NCM. Assuming that the applied voltage from the PIM tester is V_{in} , then the voltage applied to each PIM source in DM and NCM is calculated as presented below.

$$V_{iD,A} = V_{in} \dot{S}_{56} \quad (6)$$

$$V_{iN,A} = V_{in} \{ \dot{S}_{31} \dot{S}_{53} (1 + \dot{S}_{55}) + \dot{S}_{21} \dot{S}_{42} \dot{S}_{54} \} \quad (7)$$

$$V_{iD,C} = V_{in} \quad (8)$$

$$V_{iN,C} = V_{in} \{ \dot{S}_{21} \dot{S}_{42} \dot{S}_{64} + \dot{S}_{31} \dot{S}_{53} \dot{S}_{65} \} \quad (9)$$

Therein, $V_{iD,A}$ and $V_{iN,A}$ respectively denote the voltage applied to PIM source A in DM and NCM. Similarly, $V_{iD,C}$ and $V_{iN,C}$ respectively stand for the voltages applied to PIM source C. Because it is a passive circuit, $\dot{S}_{nm} = \dot{S}_{mn}$ is obtained. If each coupling condition between each antenna element and probe is kept as equal, then $\dot{S}_{42} = \dot{S}_{53}$ is obtained. Both are denoted as $\dot{S}'_C$. In addition, from the phase difference of the feed line, $\dot{S}_{21} \dot{S}_{42} \dot{S}_{64} = \dot{S}_{31} \dot{S}_{53} \dot{S}_{65}$, $\dot{S}_{21} \dot{S}_{42} \dot{S}_{54} = -\dot{S}_{31} \dot{S}_{53} \dot{S}_{55}$ is obtained. In addition, for an ideal divider, $|\dot{S}_{21}| = |\dot{S}_{31}| = |\dot{S}_{46}| = |\dot{S}_{56}| = 1/\sqrt{2}$ is obtained. Consequently, equation (10) is obtained.

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