DIRECT COMPARISON TRANSFER OF MICROWAVE POWER SENSOR CALIBRATION WITH AN ADAPTOR: MODELING AND EVALUATION

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Abstract—In this paper, calibration of a microwave power sensor with an adaptor is investigated with direct comparison transfer technique, and mathematically modeled using signal flow-graphs together with non-touching loop rules. The developed calibration model is then implemented practically with a 30 dB attenuator as the adaptor. Its performance is evaluated following the *Guide to the Expression of Uncertainty in Measurement* and also verified with the Monte Carlo method. Good agreements are observed with all the error $|E_n| \leq 0.25$ over the whole frequency range (up to 18 GHz).

1. INTRODUCTION

Direct comparison transfer technique has been widely used for microwave power sensor calibrations [1–4] since it was proposed by the National Institute of Standards and Technology, USA [1]. This technique, as shown in Figure 1(a), consists of a power source (microwave synthesizer) and a 3-port splitter or coupler which is used to minimize the source mismatch [5]. A monitoring power sensor is connected to one of the output ports of the splitter/coupler. The effective efficiency η_{DUT} and the calibration factor K_{DUT} of a device under test (DUT) are measured by alternately connecting a reference standard (with the effective efficiency η_{Std} and the calibration factor
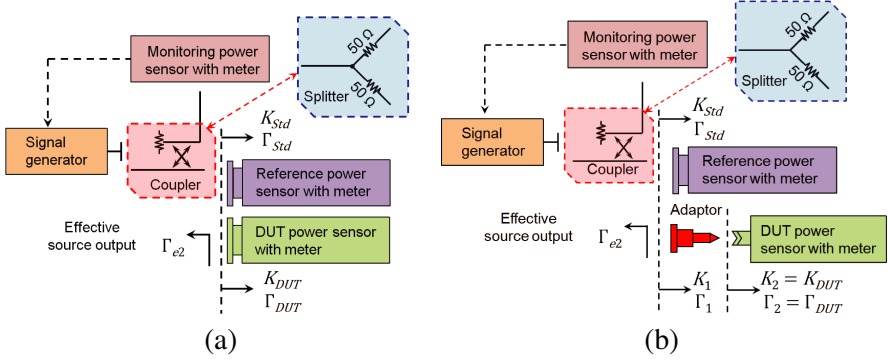
Figure 1. Calibration of a microwave power sensor by the method of direct comparison transfer using a splitter or a coupler, (a) no adaptor, (b) with an adaptor before DUT.

K_{Std}) and the DUT to another output port of the splitter/coupler. For the setup shown in Figure 1(a), the connector types of the DUT and the reference standard are kept the same.

Recently, in order to make full utilizations of the existing standards for microwave power sensor calibrations, adaptors have been used [3, 4]. To provide accurate calibration results, the adaptor effect needs to be removed. However, there is a lack of detailed analysis and theoretical background to support the practical implementations with an adaptor, and a generic model for direct comparison transfer technique with/without adaptor has therefore been proposed in our previous work [4]. To evaluate the calibration systems using the derived models, some different application scenarios were investigated. The first is for the calibration without any adaptor (as shown in Figure 1(a)). The derived model was successfully implemented in a banded WR15 (50–75 GHz) and WR10 (75–110 GHz) waveguide power sensor calibration system which is a new setup in the the National Metrology Centre (NMC) of A*STAR [6].

The second covers the calibration scenario using an adaptor (e.g., 2.4 mm to 3.5 mm adaptor, female to male adaptor, coaxial to waveguide adaptor or attenuator for different applications). We investigated the case with an adaptor before the DUT as shown in Figure 1(b) while the reference standard is alternatively connected to the splitter directly, using an existing coaxial calibration system. However, the preliminary results for this calibration scenario indicate extremely large uncertainties, and unacceptable for practical implementations as we discussed in [4]. Hence, this promotes us to

carry out further investigations.

In this paper, detailed analysis of the calibrations with an adaptor (we use a 30 dB attenuator in this study as in [7]) before a DUT is performed. This is to evaluate the performance of the newly proposed model in [4] which has not been fully validated. In the following, theoretical modeling using the signal flow graphs for the calibration scenario with an adaptor before the DUT is briefly discussed in Section 2. For simplicity, we focus on the study of the mathematical model for the calibration factor K_{DUT} of a DUT. The same methodology can be applied to the effective efficiency η_{DUT}. In Section 3, evaluation of the corresponding measurement system using the derived model is reported. Finally, conclusions of this paper are presented in Section 4.

2. THEORETICAL BACKGROUND

The *Guide to the Expression of Uncertainty in Measurement* (GUM) [8] has been widely accepted and followed for calibrating a microwave power sensor, where a model of measurement (i.e., a functional relationship between the measured variable and the set of influencing quantities) is preferred for evaluating the measurement uncertainty.

To develop a suitable measurement model for the direct comparison transfer with an adaptor before the DUT while the reference standard is alternatively connected to a splitter/coupler directly (the calibration scenario in Figure 1(b)), signal flow-graphs, as shown in Figure 2, are used together with the non-touching loop
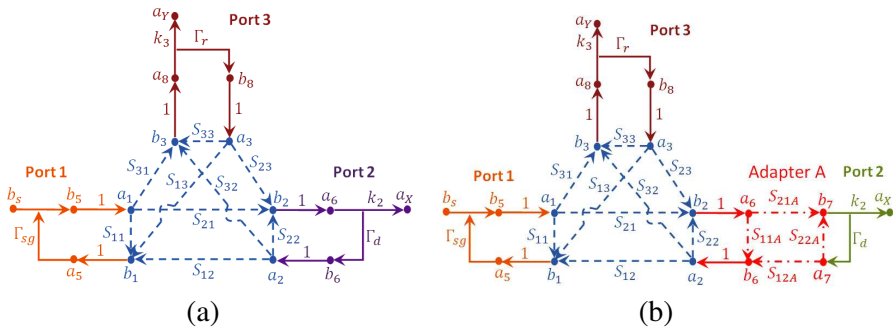

Figure 2. Signal flow graphs for the direct comparison transfer system with an adaptor before DUT as shown in Figure 1(b), (a) for the reference standard, (b) for the DUT with an adaptor.

rules [9] as reported in [4]. Here, the output port of the splitter/coupler connecting to a reference standard or a DUT with an adaptor is named as port 2, and the other output port for power leveling and monitoring is named as port 3. The calibration factor K_{DUT} of the DUT is then obtained as,

$$
K_{\mathrm{DUT}} = K_{\mathrm{Std}} \times \frac{P_{\mathrm{DUT}}}{P_{\mathrm{3DUT}}} \times \frac{P_{\mathrm{3Std}}}{P_{\mathrm{Std}}} \times \left| \frac{k_{\mathrm{2Std}}}{k_{\mathrm{2DUT}}} \right|^2
$$
$$
\times \left| \frac{1 - \Gamma_{\mathrm{DUT}} S_{22A} - \Gamma_{e2} \Gamma_{A-\mathrm{DUT}}}{S_{21A}(1 - \Gamma_{\mathrm{Std}} \Gamma_{e2})} \right|^2, \tag{1}
$$

where

- P_{DUT} and P_{3DUT} are the powers measured at port 2 using the DUT and that at port 3 using a monitoring sensor, respectively,

- P_{Std} and P_{3Std} are the powers measured at port 2 using a reference standard and that at port 3 using the same monitoring sensor as for measuring P_{3DUT},

- k_{2Std} and k_{2DUT} are some unknown terms related to the leakage of cable and connector, drift, linearity and frequency error when the reference standard and the DUT are connected to port 2,

- $\Gamma_{A-\mathrm{DUT}} = S_{11A} + \Gamma_{\mathrm{DUT}} S_{21A} S_{12A} - \Gamma_{\mathrm{DUT}} S_{22A} S_{11A}$, where Γ_{DUT} is the reflection coefficient of the DUT, and S_{ijA} is the scattering parameter (S-parameter) of the adaptor with i, $j = 1$ or 2. Γ_{Std} is the reflection coefficient of the reference standard,

- Γ_{e2} is the equivalent source reflection coefficient of the splitter (coupler) at port 2 and equal to [10]

$$
\Gamma_{e2} = S_{22} - \frac{S_{21} S_{32}}{S_{31}}. \tag{2}
$$

Here S_{kl} is the S-parameter of the 3-port splitter/coupler with k, $l = 1$, 2 or 3.

3. MEASUREMENT RESULTS AND ANALYSIS

3.1. Measurement System and Setup

The derived calibration model in (1) was implemented with a coaxial microwave power sensor calibration system, which is a physical realization of the direct comparison transfer with an adaptor in Figure 1(b). During the evaluation of the calibration model in (1), an Agilent 8481D power sensor (power range: 100 pW–10 µW and frequency range: 10 MHz–18 GHz) is used as a DUT sensor. The

reference standard is a thermistor mount fitted with a type-N connector and calibrated in term of the effective efficiency at $1\,\text{mW}$ directly by means of a micro-calorimeter, which is a primary microwave power standard at NMC, A*STAR. To assist the transfer of key referenced parameters (i.e., η_{Std} and K_{Std}) of the thermistor mount to the Agilent 8481D sensor, a $30\,\text{dB}$ attenuator which is a 2-port adaptor is used. It is noted that, an Agilent 8481A sensor (power range: $1\,\mu\text{W}$–$100\,\text{mW}$ and frequency range: $10\,\text{MHz}$–$18\,\text{GHz}$) is used for power leveling and monitoring at port 3 of the power splitter.

3.2. Results and Analysis

The calibration factor K_{DUT} of the DUT can be estimated using the calibration model in (1) with the coaxial system described above, while the measurement uncertainty of K_{DUT} needs to be evaluated following some internationally recommended guidelines [8, 11]. The functional relationship between the measured variable (K_{DUT}) and the set of influencing quantities (K_{Std}, Γ_{DUT}, Γ_{e2}, Γ_{Std}, S_{21A}, and S_{12A} etc.) as shown in (1) is used.

3.2.1. Evaluating the Measurement Uncertainty

For simplicity in the following analysis, the measured variable (K_{DUT}) is assigned a simple symbol y, and the influencing physical quantities (K_{Std}, Γ_{DUT}, Γ_{e2}, Γ_{Std}, S_{21A}, and S_{12A} etc. in (1)) are assigned some simple symbols (x_1, x_2, x_3, ..., x_N) with a relationship,

$$y = f(x_1, x_2, x_3, \ldots, x_N). \tag{3}$$

According to the *Law of Propagation of Uncertainty* in the GUM [8], the combined standard uncertainty u_c associated with y can be obtained from the standard uncertainties of x_1, x_2, x_3, ..., x_N through

$$u_c = \sqrt{\sum_{i=1}^{N} u_i(y)^2}, \tag{4}$$

where $u_i(y)$ is the uncertainty of y due to the standard uncertainty $u(x_i)$ of x_i and defined as

$$u_i(y) = \left| \frac{\partial y}{\partial x_i} \right| u(x_i). \tag{5}$$

For the standard uncertainty $u(x_i)$ of x_i, either *Type-A* or *Type-B* evaluation can be used according to the GUM [8]. For the *Type-A* method, the standard uncertainty is evaluated by the statistical analysis of series of observations, while for the *Type-B* method, the

standard uncertainty is obtained from other information including previous measurement data, specifications from manufacturers, data provided in calibration and other certificates, and uncertainties assigned to reference data taken from handbooks etc.. It is noted that in this study for the complex-valued microwave quantities such as S-parameter and reflection coefficient, their standard uncertainties are evaluated with the assumption of zero correlation between their real and imaginary parts [12, 13].

To verify the accuracy of the GUM method, the Monte Carlo Method (MCM) [11] as illustrated in Figure 3 has been used for propagating the uncertainties of the influencing quantities (K_{Std}, Γ_{DUT}, Γ_{e2}, Γ_{Std}, S_{21A}, and S_{12A} etc. in (1)) to the measured variable (K_{DUT}). During the Monte Carlo simulation (with the number of trials $M = 1000000$), all the influencing quantities are assumed to be Gaussian distributed with the input information directly from the measurement estimates respectively. Examples of the simulated results using the MCM Method are shown in Figure 4. It is also found that the
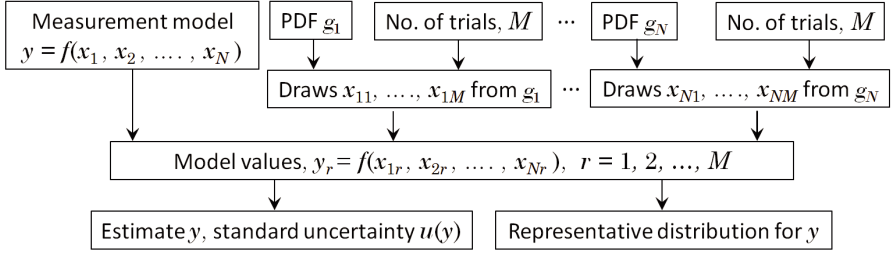

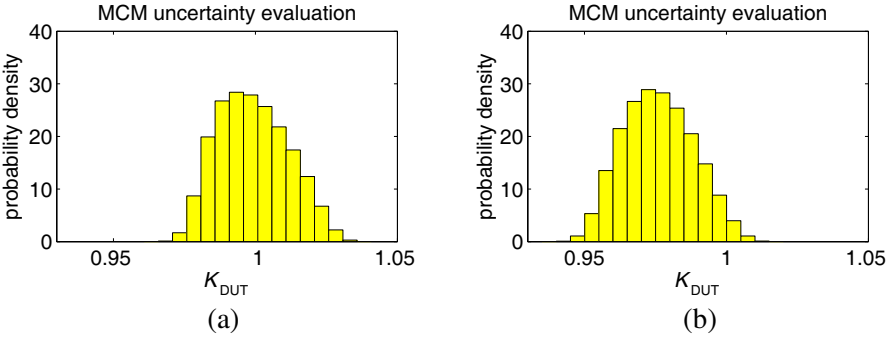**Figure 3.** The Monte Carlo method [11].

Figure 4. Examples of the simulated results using the Monte Carlo Method (MCM) [11], (a) 50 MHz, (b) 14 GHz.

representative distribution for K_{DUT} (as shown in Figure 4) from the Monte Carlo method approximates to be a Gaussian function. This is because the recommended guideline [11] is the *Law of Propagation of Distributions* essentially, which propagates the assigned probability distribution function (PDF) to the influencing quantities to the desired parameter (K_{DUT} in this study).

3.2.2. Comparing the Measurement Uncertainties Evaluated Using the GUM and the MCM

The evaluated results using the GUM and MCM methods are plotted in Figure 5. It is observed from Figure 5 that the measurement uncertainties evaluated by both the methods are close to each other. However, there are some slight differences in the estimates for K_{DUT}, and the differences become obvious at higher frequencies. To
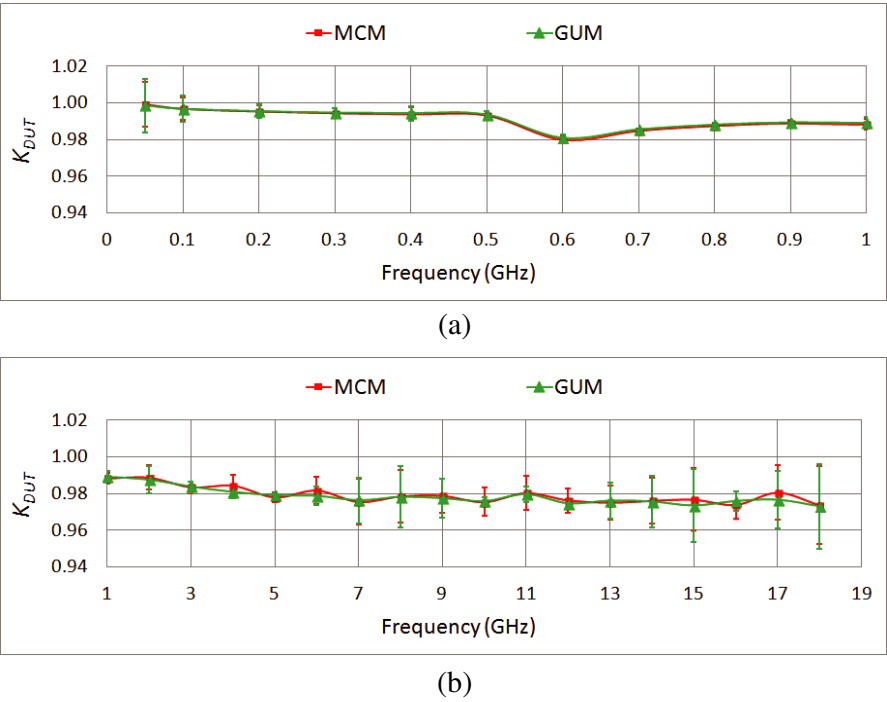

(a)

(b)

Figure 5. Calibration of an Agilent 8481D power sensor with a 30 dB attenuator using the direct comparison transfer (with the associated combined standard uncertainty displayed), (a) 50 MHz to 1 GHz, (b) 1 GHz to 18 GHz.

compare the performances of both the methods quantitatively, an error parameter E_n which is normalized with respect to the stated uncertainties, is used as the following [14],

$$E_n = \frac{\delta_A - \delta_B}{\sqrt{U_A^2 + U_B^2}} \qquad (6)$$

where δ_A and δ_B are the estimates for K_{DUT} using the GUM and MCM methods respectively, and U_A and U_B are the corresponding expanded uncertainties (equal to $2u_c$ at a level of confidence of approximately 95% assuming a Gaussian distribution in this study). According to [14], the discrepancies between the evaluated results are acceptable when $|E_n| \leq 1$.

The calculated E_n for comparing the measurement uncertainties evaluated by the GUM and the MCM in Figure 5 are plotted in Figure 6. From Figure 6, it is observed that there are very good agreements between the results in the whole frequency range as all the $|E_n| \leq 0.25$. These results demonstrate the capability of the calibration model in (1).
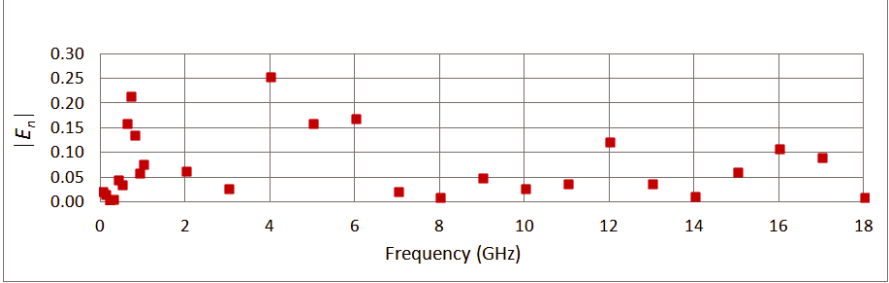

Figure 6. The calculated E_n with normalization.

4. CONCLUSIONS

In this paper, calibrating a microwave power sensor with an adaptor using direct comparison transfer technique has been mathematically modeled and practically evaluated.

The developed measurement model was implemented with a 30 dB attenuator as a 2-port adaptor. Its performance was evaluated by the GUM and the MCM. The observed good agreements (all the $|E_n| \leq 0.25$) demonstrate the capability of the calibration model in (1). However, to be a reliable model for providing the calibration services to the industry, calibration scenarios using other adaptors (e.g., female

to male adaptor, coaxial to waveguide adaptor etc.) are required and will be investigated in the future.

ACKNOWLEDGMENT

REFERENCES

1. Weidman, M. P., "Direct comparison transfer of microwave power sensor calibration," *NIST Technical Note 1379*, 1996.

2. Ginley, R, "A direct comparison system for measuring radio frequency power (100 kHz to 18 GHz)," *Measure*, Vol. 1, No. 4, 46–49, 2006.

3. Kang, T. W., J. H. Kim, J. Y. Kwon, et al., "Direct comparison technique using a transfer power standard with an adapter and its uncertainty," *2012 Conference on Precision Electromagnetic Measurements*, 728–729, Washington DC, USA, 2012.

4. Shan, Y., Y. S. Meng, and Z. Lin, "Generic model and case studies of microwave power sensor calibration using direct comparison transfer," *IEEE Transactions on Instrumentation and Measurement*, Vol. 62, 2013, DOI:10.1109/TIM.2012.2225961.

5. Engen, G. F., "Amplitude stabilization of a microwave signal source," *IRE Transactions on Microwave Theory and Techniques*, Vol. 6, No. 2, 202–206, 1958.

6. Meng, Y. S., Y. Shan, and H. Neo, "Development of a waveguide microwave power sensor calibration system at NMC," *2012 Asia-Pacific Symposium on Electromagnetic Compatibility*, 745–748, Singapore, 2012.

7. Yhland, K., J. Stenarson, and C. Wingqvist, "Power sensor linearity calibration with an unknown attenuator," *2010 Conference on Precision Electromagnetic Measurements*, 769–770, Daejeon, Korea, 2010.

8. BIPM, IEC, IFCC, ILAC, ISO, et al., "Evaluation of measurement data — Guide to the expression of uncertainty in measurement," JCGM 100 : 2008 (GUM 1995 with minor corrections), Joint Committee for Guides in Metrology, 2008.

9. Pozar, D. M., *Microwave Engineering*, Addison-Wesley, 1993.

10. Fantom, A., *Radio Frequency and Microwave Power Measurement*, Peter Peregrinus Ltd., UK, 1990.

11. BIPM, IEC, IFCC, ILAC, ISO, et al., "Evaluation of measurement data — Supplement 1 to the 'Guide to the expression of uncertainty in measurement' — Propagation of distributions using a Monte Carlo method," JCGM 101 : 2008, Joint Committee for Guides in Metrology, 2008.

12. Meng, Y. S., Y. Shan, and H. Neo, "Evaluation of complex measurement uncertainty in polar coordinate for equivalent source reflection coefficient," *2012 Conference on Precision Electromagnetic Measurements*, 116–117, Washington DC, USA, 2012.

13. Meng, Y. S. and Y. Shan, "Measurement uncertainty of complex-valued microwave quantities," *Progress In Electromagnetics Research*, Vol. 136, 421–433, 2013.

14. APLAC PT001, "Calibration interlaboratory comparisons," Asia Pacific Laboratory Accreditation Cooperation-Proficiency Testing Committee, 2008.