Error Model for Insertion Loss Measurement in Testing of Balanced Twisted-Pair Cabling: A Complete Expression and Its Simplification

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Abstract

This paper presents some recent works on development of a new error model for insertion loss measurements in testing of balanced twisted-pair copper cabling. Based on the signal flow-graph for practical testing scenario, a complete expression of the measurement error model has been proposed in this study. Its simplified form is thereby suggested for industry applications up to 2 GHz. Comparing to the current error model which was proposed at lower frequency, the new error model considers more error terms which become significant at higher frequency.

1. Introduction

Precision electromagnetic measurements have been increasingly demanded by the industry recently for various applications. One of them is the electromagnetic transmission over a twisted-pair copper cable for high data-rate information technology. For the twisted-pair copper cabling installation, performance specifications as required by some international standards (e.g., IEC 61935-1 [1] published by the International Electrotechnical Commission [IEC]) need to be followed.

Due to rapid developments in high data-rate transmission scheme over a copper cable (e.g., 40-Gbps data transmission), the current specifications in IEC-61935 standard [1] covering a frequency up to 600 MHz need to be revised accordingly. A draft revision of IEC-61935 standard [2] has been circulated for comments recently. However, there is no revision to the error model when calculating the measurement uncertainty. For higher frequency applications (e.g., 2 GHz for a Category-8 cabling), some error terms which were ignored for low frequency measurements need to be considered. In this paper, measurement error model for insertion loss which is a key performance indicator for twisted-pair copper cabling as proposed in [1] will be re-examined.

In the following, testing of balanced twisted-pair copper cabling will be introduced in Section 2 with a discussion on the current error model for insertion loss measurements. In Section 3, detailed derivation of a complete expression for insertion loss error model will be presented. Its simplified form is also discussed for practical applications. This is followed by performance comparison and analysis in Section 4. Finally, conclusion of this paper is given Section 5.

2. Research Background of Twisted-Pair Cabling

Twisted-pair cable is composed of two insulated copper wires twisted around each other and bundled together with other 3 pairs in a jacket. Electromagnetic data transmission over a twisted-pair copper cable will be attenuated before it arrives at the destination as shown in Figure 1. The attenuation (preferred as 'Insertion Loss' in cabling) could severely degrade the cabling performance, and normally can be measured in terms of scattering parameters (S-parameter) using a network analyzer. It is noted that different from single-ended measurements (i.e. unbalanced measurements referenced to the ground) [3], testing of a twisted-pair copper cabling is differential (i.e. balanced). A pair of field testers has been adopted by the industry at both the terminations ('Local' versus 'Remote') of an installed cable to function as a network analyzer in a laboratory.

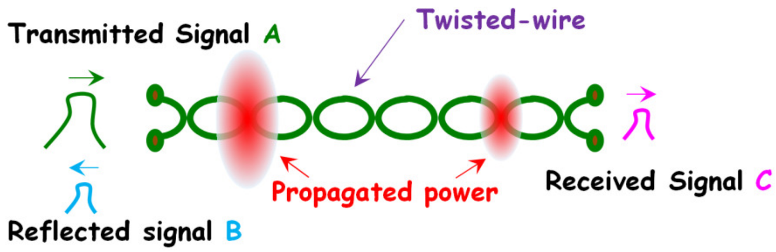

Figure 1: Demonstration of the electromagnetic-wave propagation along a twisted-pair copper cable.

2.1 Field Testing of Balanced Twisted-Pair Cabling

For the field testing of balanced twisted-pair copper cabling, the industry has adopted a typical measurement configuration as shown in Figure 2. A pair of field testers is used at the local and remote cable terminals to evaluate the cabling performance in terms of differential S-parameters (S_{ddij} with i, j = 1 or 2). From the configuration, it is found that impedance mismatch at testers and also cable (link) connecting interfaces can introduce significant errors in the measurement results of insertion loss. Therefore their influences need to be properly characterized and modeled, and will be focused in this paper.

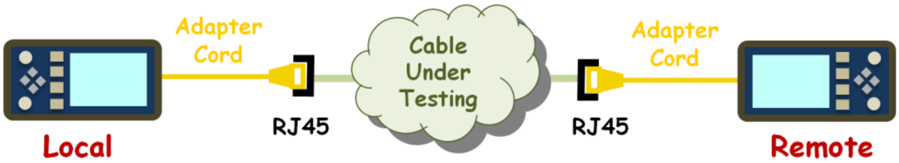

Figure 2: Measurement configuration using a pair of field testers.

2.2 Current Error Model for Insertion Loss Measurement

IEC-61935 standard [1-2] has specified an error model for insertion loss (IL) measurements in testing of balanced twisted-pair copper cabling. The error model is shown below,

$$Accuracy_{IL} = E_{d,IL} + 20\log_{10}\left[1 + 10^{\frac{-E_{RL,tester}}{10}} + 2\times 10^{\frac{-\left(E_{RL,tester}+E_{RL,link}\right)}{20}}\right] \quad (1)$$

where $Accuracy_{IL}$ is the estimated accuracy of the insertion loss measurement function in dB, $E_{d,IL}$ is the dynamic accuracy of the tester for insertion loss, $E_{RL,tester}$ is the source/load return loss of the tester in dB, and $E_{RL,link}$ is the return loss of the link in dB. It is noted that the error model (1) is a simplified model for industry applications with a covering frequency up to 600 MHz in [1]. It may not be applicable at higher frequency (e.g., up to 2 GHz). This is because its simplification may ignore some error terms which become significant at higher frequency.

3. Derivation of Error Model for Higher Frequency Applications

For insertion loss measurements in certifying balanced twisted-pair copper cabling, a simplified signal flow-graph below can be used to interpret the measurement configuration as shown in Figure 2,

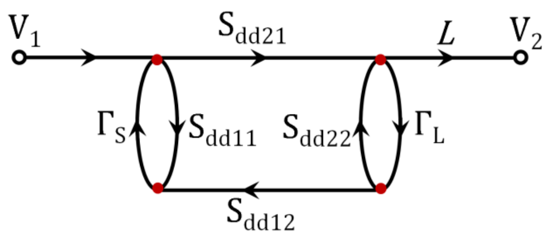

Figure 3: Simplified signal flow-graph for insertion loss measurements in the balanced cabling.

As shown in Figure 3, Γ_S and Γ_L are the residual calibration errors for the source match and the load match (due to the impedance mismatch) respectively and L is for the transmission tracking in 2-port measurements (preferred to be the dynamic accuracy of a field tester in cabling). S_{dd11}, S_{dd21}, S_{dd12} and S_{dd22} are the actual differential S-parameters of the cabling. A leakage path existing for a normal network analyzer in the laboratory is ignored in Figure 3 since the field testers are separated with a long enough distance in practical measurements.

Using the non-touching loop rule [4], a complete form for the relationship between the input voltage V_1 and the output voltage V_2 can be obtained,

$$\frac{V_2}{V_1} = L\left\{\frac{S_{dd21}(1-\Gamma_S\Gamma_L)}{(1-S_{dd11}\Gamma_S)(1-S_{dd22}\Gamma_L) - S_{dd12}S_{dd21}\Gamma_S\Gamma_L}\right\}. \quad (2)$$

It is noted that V_2/V_1 is the reported value by a pair of calibrated field testers for the insertion loss measurements, while the quantity of interest for checking cabling installation is S_{dd21}. The difference between (V_2/V_1) and S_{dd21} is the measurement error introduced by a pair of field testers.

3.1 A Complete Expression of Error Model

From (2), we can get the measurement error ($M.E.$) for insertion loss in a linear format as,

$$M.E._{IL} = \frac{1}{S_{dd21}}\left(\frac{V_2}{V_1}\right) = L\left\{\frac{1-\Gamma_S\Gamma_L}{(1-S_{dd11}\Gamma_S)(1-S_{dd22}\Gamma_L)-S_{dd12}S_{dd21}\Gamma_S\Gamma_L}\right\}. \quad (3)$$

The second term, $\left\{\frac{1-\Gamma_S\Gamma_L}{(1-S_{dd11}\Gamma_S)(1-S_{dd22}\Gamma_L)-S_{dd12}S_{dd21}\Gamma_S\Gamma_L}\right\}$ of (3) is the complete error contribution due to the impedance mismatch arising from the residual source and load reflection coefficients and the input and output reflection coefficients from the balanced twisted-pair copper cabling installation. It has a similar form as reported in [5] or more originally in [6].

Converting (3) to the decibel (dB) unit ($Accuracy_{IL} = 20\log_{10}(M.E._{IL})$), we can obtain the following

$$Accuracy_{IL} = E_{d,IL} + 20\log_{10}\left\{\frac{1-\Gamma_S\Gamma_L}{(1-S_{dd11}\Gamma_S)(1-S_{dd22}\Gamma_L)-S_{dd12}S_{dd21}\Gamma_S\Gamma_L}\right\}. \quad (4)$$

Here, $E_{d,IL}$ is the dynamic accuracy of the tester in dB as introduced previously, and equal to $|20\log_{10}(L)|$.

3.2 Its Simplification

Since the testing of a balanced twisted-pair copper cabling is mainly to check its compliance with the regulation and indicates out ‘Pass’/‘Fail’ precisely. The worst case for the measurement error (maximum possible error by an ignorance of the phase relations as in [6]) should be considered and can approach to be,

$$Accuracy_{IL} = E_{d,IL} + 20\log_{10}\left\{\frac{1+|\Gamma_S||\Gamma_L|}{1-|S_{dd11}||\Gamma_S|-|S_{dd22}||\Gamma_L|-|\Gamma_S||\Gamma_L|(|S_{dd11}||S_{dd22}|+|S_{dd12}||S_{dd21}|)}\right\}. \quad (5)$$

With the assumptions of $\Gamma_S = \Gamma_L$ for an identical model of field tester, and $S_{dd11} = S_{dd22}$ and $S_{dd12} = S_{dd21}$ for a symmetrical network, the error model (5) can be simplified to be,

$$Accuracy_{IL} = E_{d,IL} + 20\log_{10}\left\{\frac{1+10^{\frac{-E_{RL,tester}}{10}}}{1-2*10^{\frac{-E_{RL,link}-E_{RL,tester}}{20}}-10^{\frac{-E_{RL,tester}-E_{RL,link}}{10}}-10^{\frac{-E_{RL,tester}-E_{IL,link}}{10}}}\right\}. \quad (6)$$

where $E_{RL,tester} = -20\log_{10}(|\Gamma_S|)$ is the residual source/load return loss of a tester in dB, $E_{RL,link} = -20\log_{10}(|S_{dd11}|)$ is the return loss of the link in dB, and $E_{IL,link} = -20\log_{10}(|S_{dd21}|)$ is the insertion loss of the link in dB. Comparing to (1) in the current IEC standard [1-2], an additional contribution from $E_{IL,link}$ is introduced in the newly proposed error model (6).

4. Performance Comparison and Analysis

For performance comparisons between the current error model (1) and the newly proposed error model (6) for insertion loss measurements, the input parameters ($E_{d,IL}$, $E_{RL,tester}$, $E_{RL,link}$, and $E_{IL,link}$) are either from the required specifications for testing of balanced cabling in [1-2] or those under proposal for the frequency up to 2 GHz. The practical performance parameters of a field tester are not considered in this study. A 30-m link is used in the comparison.

Figure 4 presents the calculated performance limits for insertion loss measurements using the current error model (1) and the newly proposed error model (6). From the results, it is clearly observed that the calculated results using the new error model are higher than those from the current error model, and their difference is increasing correspondingly when the operating frequency increases. This is under expectation since the new error model considers more error terms which become more significant at higher frequency, as compared with the current error model which was proposed for lower frequency applications.

It is also noted that both the models (1) and (6) produce the error results which are much higher than the evaluated uncertainty for vector network analyzer (VNA) measurements in a laboratory (e.g., in [3]). This is because both the models (1) and (6) consider the worst case with 100% level of confidence, while the normal circumstance for VNA measurements only requires an uncertainty evaluation at a level of confidence of approximately 95%.

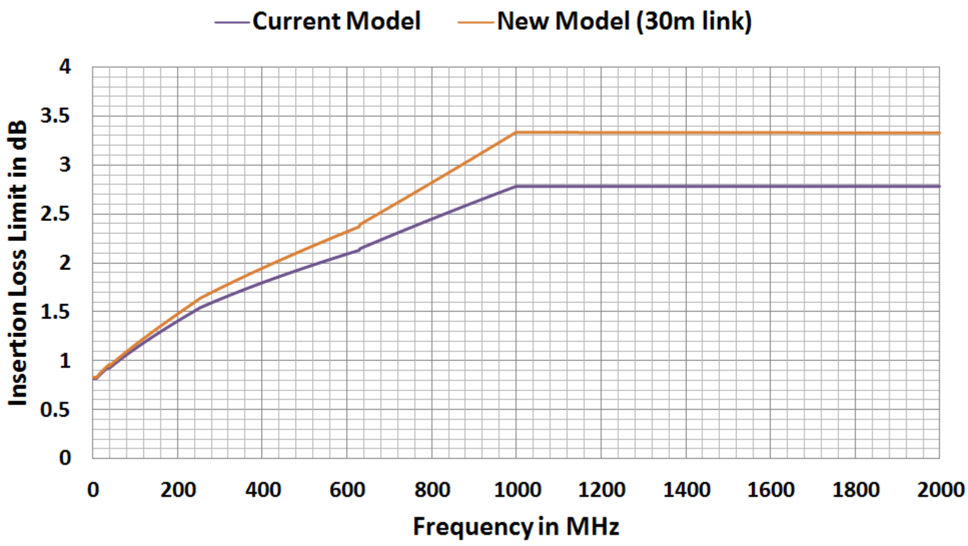

Figure 4: Limit comparisons of the current error model (1) and the newly proposed error model (6) for insertion loss measurements.

5. Conclusion

In this paper, a recent proposal of a new error model for insertion loss measurements in testing of balanced twisted-pair copper cabling was reported. A complete expression of the error model and its simplified form have been suggested for industry applications up to 2 GHz. A preliminary comparison has been performed using the specifications from the current IEC standards or those under proposal. It is clear that some error terms which become significant at higher frequency should be considered. Further evaluation of the proposed error model with practical specifications of a field tester will be carried out in the near future.

6. Acknowledgments

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7. References

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