Robust Extended Unterminated Line (EUL) Crosstalk Characterization Techniques for High-Speed Interconnect

Yuandong Guo[1], DongHyun Kim[1], Jiayi He[1], Xiaoning Ye[2], Albert Sutono[2], Vijay Kunda[2], Amy Luoh[2], Zurab Kiguradze[1], Li Shen[1], and Jun Fan[1]

[1]Electromagnetic Compatibility Laboratory, Missouri University of Science and Technology, Rolla, Missouri, USA

[2]Datacenter Group, Intel Corporation, Portland, Oregon, USA

Email: ydggdd@mst.edu

***Abstract*—Extend Unterminated Line (EUL) structure allows crosstalk measurements with perfect termination and halves the number of test ports required by the traditional method. Therefore, EUL is a time-efficient and convenient structure for a test vehicle design of high-speed interconnects. In this paper, the potential errors in the EUL measurement are analyzed. In addition, an error detection method to check for causality, passivity and reciprocity is demonstrated. It is the first time to propose the best practices and robustness-enhancement techniques for EUL crosstalk characterization.**

Keywords—signal integrity, crosstalk, extend unterminated line, D-probe, causality, passivity, reciprocity.

I. Introduction

Crosstalk is a critical concern in signal integrity analysis and is known as one form-factor of jitter in high-speed interconnections [1]. Traditional method of crosstalk measurement always requires a vector network analyzer (VNA) with multiple test ports and perfect terminations at non-measured ports of a DUT, which results in extended measurement time, especially for the crosstalk measurements of differential transmission lines. Previously, extended unterminated line (EUL) structures have been proposed to overcome the inherent drawbacks of the traditional crosstalk measurement method. It can attain perfect termination conditions for non-measured ports by introducing an unterminated transmission line with the same characteristic impedance as the coupled traces. Thus, the test ports required in an EUL measurement are reduced to half compared to that of the traditional measurement method [2]. EUL structure has been considered as an efficient yet accurate approach in crosstalk testing vehicle design for high-speed applications.

Crosstalk characterization is sensitive to measurement errors due to low level signals, which necessitates robust measurement techniques in order to obtain valid data for signal integrity analysis. Unreliable crosstalk characterization may lead to wrong design decisions influencing high-speed interconnect design and optimization. Therefore, potential errors in EUL measurement must be analyzed, and an error detection method with best practices must be proposed to prevent or correct the errors during EUL measurements. This paper focuses on the robustness-enhancement techniques for crosstalk characterization by using EUL structure.

Microprobe is widely used in high-frequency measurements and it has a comparable measurement quality with SMA connectors. In general, the latter is considered to be less efficient than the former. As a type of microprobe, D-probe only requires two signal pins compared to a ground-signal-signal-ground microprobe. Since the common-mode information of a DUT is not needed for crosstalk characterization, D-probe is typically suitable for differential measurements due to its robust mechanical structure, excellent electrical performance and smaller landing space on a print circuit board (PCB) [3]. In this paper, D-probe and its corresponding launch pad are adopted as a recommended setup in the testing vehicle design and crosstalk measurements.

EUL structure can be implemented for both near-end (NEXT) and far-end crosstalk (FEXT) characterization [2]. Due to the similarities between NEXT and FEXT measurements, this paper focuses on FEXT measurement only. The FEXT measurement setup and potential EUL measurement errors are illustrated and discussed in Section II. Error detection methods are proposed in Section III with physical interpretations. The best practices to prevent measurement errors are demonstrated in Section IV.

II. EUL Setup for FEXT Measurement and Potential Measurement Errors

A. FEXT Measurement Setup with EUL Structure

For two coupled differential striplines, the recommended setup of FEXT measurement using EUL structure and D-probe is described in Fig. 1. The differential signal pairs and EUL patterns are manufactured on a PCB indicated by the solid box in Fig. 1 while the dashed box illustrates the DUT. The launch pads are intentionally separated from the D-probes for clear representation.

As mentioned in the previous section, the advantages of utilizing EUL pattern are the reduction of required VNA ports and perfect terminations at the non-measured ports of the DUT, which can be clearly observed in Fig. 1.

B. Potential Errors in EUL Measurement

Crosstalk characterization requires extreme care as a relatively small error can result in physically impossible measurement result. In the example exhibited in Fig. 2, causality issue can be observed resulting from a careless calibration. Because of the gradually increasing offset before the occurrence of FEXT, despite its relatively small magnitude less than 0.2 mV (approximately -14 dBmV), the measured FEXT result is not reliable because the FEXT magnitude is even smaller than the gradual offset.

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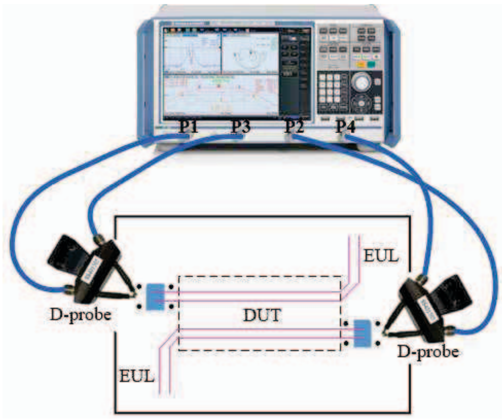

Fig. 1 The FEXT measurement setup using EUL structure and D-probes.

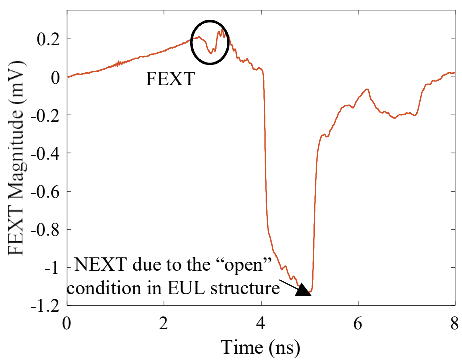

Fig. 2 An example showing poor FEXT characterization with careless calibration.

It is known that there are three error types in a VNA measurement which are systematic, random and drift errors. Random error is unpredictable but can be averaged out during measurement. Drift error describes the variations in the performance of a measurement system and is predominantly caused by temperature changes [4]. It is a good practice that checking measurement repeatability occasionally after calibration is done to evaluate drift errors.

Systematic error is mainly contributed by the imperfections in the test setup and instruments and can be eliminated by a careful calibration [5]-[7]. Unnecessary or intensive operator interaction during calibration process can lead to larger systematic error due to multiple connections between different coaxial cables and connectors. Therefore, electronic calibration (E-Cal) with minimum number of required connections is recommended in this paper as a substitution of mechanical calibration standards.

Poor lab techniques can increase the risk of large measurement error and degrade measured data quality, causing causality and passivity problems [4]. Thus, it is important and recommended to frequently inspect the connector and cable conditions and the quality of calibration standards.

Crosstalk characterization requires higher dynamic range of a VNA to enable higher precision during measurement. Within the highest input power limit of a VNA, greater dynamic range can be achieved typically by reducing the intermediate frequency bandwidth (IF BW) or by using the averaging function [8]. However, the trade-off is that both of the methods increase measurement time.

The effect of the test fixtures which include the D-probes, lead-in traces on the PCB and interconnections contributes to the errors in the EUL measurement shown in Fig. 1. Rigorous de-embedding process can be employed to remove the unwanted artifacts and expose the electrical performance of DUT [9]-[11].

A perfect VNA measurement which contains continuous data from DC to infinity in frequency-domain is not realistic [12]. Due to the limited frequency band and available data only at finite discrete points during EUL crosstalk characterization, the measured S-parameters using the setup demonstrated in Fig. 1 can never be treated as ideal. S-parameter quality will be examined and estimated in Section III, which is especially important for EUL crosstalk characterization.

III. Error Detection in EUL Characterization

Any physically valid passive network must be causal and reciprocal [13]. Namely, there are three important properties inside the S-parameters of EUL measurement: causality, passivity and reciprocity. If the measured data violates any of the physical rules, the crosstalk characterization results may not be reliable, which may result in wrong design decisions in high-speed interconnect analysis.

Conceptually, causality demonstrates the intuitive relationship of cause and consequence for a physical network. Explicitly, system output can only be observed after the input is applied. A causal transfer function of a system with real part $U(\omega)$ and imaginary part $V(\omega)$ should satisfy the Kramers-Kronig relationship described in (1), which reveals that the real and imaginary parts are not independent and can be reconstructed from each other [14].

$$V(\omega) = -\frac{1}{\pi}\int_{-\infty}^{+\infty} \frac{U(\omega')}{\omega - \omega'} d\omega$$
$$U(\omega) = \frac{1}{\pi}\int_{-\infty}^{+\infty} \frac{V(\omega')}{\omega - \omega'} d\omega \quad (1)$$

The causality of the data obtained in EUL crosstalk measurement is evaluated using (2) after converting the transfer function into time domain to acquire impulse response [14]. The results are typically expressed in percentage.

$$Causality(h) = 1 - \frac{\sqrt{\int_{-\infty}^{\tau} h^2(t)dt}}{\sqrt{\int_{-\infty}^{+\infty} h^2(t)dt}} \quad (2)$$

Fig. 3 demonstrates the comparisons in both frequency and time domains of the FEXT measured on the same EUL structure where the data of "poor measurement" suffers severe causality issue. The causality of "poor measurement" is 85.0% according to (2) indicating that the measurement has to be conducted again. On the same trace, "good measurement" results in causality as high as 98.9%. The time domain FEXT waveforms are obtained through inverse Fast Fourier Transform and after windowing out the residual of NEXT response. Despite the fact that all VNAs have causality issue, one can always define a criteria to identify whether measured data is reliable. As mentioned in Section II, exercising good lab techniques can help reduce the risk of experiencing causality issue.

EUL structures used for crosstalk characterization are

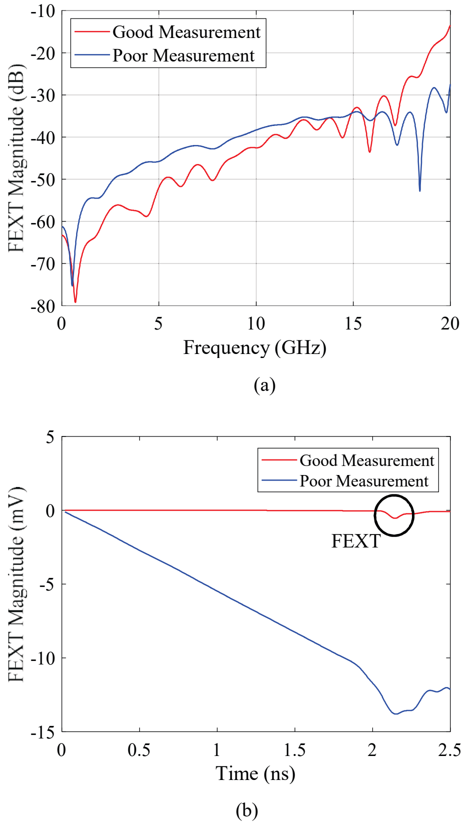

Fig. 3 Comparisons of FEXT between "good" and "poor" measurements for the same DUT: (a) frequency domain comparison, (b) time domain comparison.

passive and the eigenvalue magnitudes of S-parameter should not exceed 1. For a given measured S-parameter matrix, the construction process of $S_{passive}$ matrix is proposed in [13], in which the elements whose magnitudes are greater than 1 are identified and normalized so that in the constructed $S_{passive}$ matrix no element in the diagonal eigenvalue matrix has a magnitude beyond 1. Similarity metric is applied to $\Delta S_{passive} = S_{measure} - S_{passive}$ in time domain to estimate the passivity of measured data. A cautious calibration and smooth transitions from coaxial cables to PCB transmission lines may reduce the risk of bearing passivity issue [12].

PCB dielectric employs reciprocal materials. Thus, reciprocity is another important property in EUL structures. A reciprocal S-parameter matrix should equal to its transposed matrix [13]. The reciprocity of measured S-parameter can be estimated from the difference between $S_{measure}$ and $S_{measure}^{T}$.

IV. Best Practices to Prevent Measurement Errors

The best practices presented below are based on the analysis in the previous sections and the measurement experience of the authors. The following process is proposed for a robust EUL characterization:

1) A warmup phase is necessary to ensure a VNA is operating in thermal equilibrium condition. To assure high dynamic range in EUL characterization, low IF BW and the averaging function are generally required.

2) Routinely check the coaxial cables, connectors, adaptors and quality of interconnects. Clean the contaminated contacts.

3) E-cal is recommended and always evaluate VNA calibration quality before performing EUL measurement.

4) Apply the de-embedding method in [9]-[11].

5) Use the error detection methods proposed in this paper to identify the reliability of measurement data.

V. Conclusions

This paper investigates the potential error sources during EUL measurement and proposes error detection methods and best lab practices for robust EUL crosstalk characterization. For the first time, robustness-enhancement techniques for EUL crosstalk characterization is proposed and verified using measurement results.

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