SIMPLIFIED EQUATIONS OF A 4-PORT SCATTERING PARAMETER MODEL FOR CHARACTERIZING 4-PAIR CABLING SYSTEMS OF LOCAL AREA NETWORKS

Chun-Wen Paul Huang, Charles E. Smith, and Atef Z. Elsherbeni
Electrical Engineering Department, University of Mississippi
University, MS 38677
E-mail: atef@olemiss.edu

Bernie Hammond
Thomas and Betts Corporation
8155 T&B Boulevard
Memphis, TN 38125

Abstract-**This paper presents a set of simplified equations based on a 4-port scattering parameter (S-parameter) model for characterizing digital telecommunication cabling systems. These equations are simplified form multistage cascade S-parameter matrices. Excellent agreements between measurements and the computation results from the proposed equations with the S-parameters of components of a multi-stage cascaded cabling system are observed. These equations not only can reduce the computation burdens in comparison with traditional methods for S-matrix computations, but also can provide insights of the contributions of the S-parameters at each stage in the net cross-talk, return loss, and insertion loss of a cabling system. In addition, these equations can not only be used to compute the component specifications when the system performance is specified, but also can be used to obtain the de-embedded system characteristics by subtracting the known characteristic of the adapting components.**

Introduction

With the advancements of digital technologies, there are tremendous demands for improving the computer networking. The most current local area networks (LANs) inside buildings are built by interconnecting workstations, personal computers and telecommunication hubs with cabling systems. However, these cabling systems are lossy multi-conductor transmission line systems. High-speed digital signals are always severely distorted after traveling through the cabling systems, because of the relative small signal-to-noise ratio at the higher frequency spectra resulting from both the enormous propagation attenuation and pair-to-pair cross-talk at high frequencies. The small signal-to-noise ratio at high frequency spectra of imperfect cabling systems not only limits the networking speed, but also increases the design profiles of the networking circuitry especially on echo canceling and signal error corrections. The most widely adopted cabling systems in local area networks today are the 4-pair twisted pair cables and 4-pair connecting hardware, which are characterized using scattering parameters (S-parameters) [1]. The cabling system qualifications are also done by measuring the S-parameters of the systems. Numerous field and laboratory tests are done for installation qualification and system design verifications. Therefore, there is a need to develop simulation techniques to not only predict cabling system performance when the components are known, but also provide insights for the interactions between the S-parameters of each component.

In most circuit simulators, the transmission matrix method [2] is adopted to calculate the performance of a cascaded multi-stage circuit when the component at each stage is specified. For simulating a multi-port cascaded system, the transmission matrix at each stage, defined in voltage and current at each port, is multiplied with the next stage, and the product matrix of all transmission matrices contains the characteristics of the cascaded multi-port system. However, cabling components and systems are characterized in scattering parameter [1] instead of voltages and currents. In [3], methods are introduced to re-express the transmission matrices in scattering parameters and the transformation of transmission parameters to S-parameters. Using the transmission matrix method and transmission parameters for S-parameter transformation to characterize a multi-stage cabling system, 8 by 8 matrix operation is required. However, sometimes, the cabling system is only tested partially at the worst cross-talk pairs for all the test parameters, which are between the pair of contacts number 3 and 6 and the pair of contacts number 4 and 5 for a RJ-45 cabling system. Therefore, 8-port transmission model is too cumbersome for applications. In addition, the computed cascaded results can not provide the relations between the parameters at each junction, which is very important information for component designer to tune the characteristics to meet the system specifications. In this paper, a 4-port scattering parameter model is presented and verified. With this

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model, 4-pair (8-port) cabling systems are not only accurately modeled by a much simplified 4-port model, but also provide the insights of the interactions between S-parameters from each component.

Methodology

The proposed method is a simplified model based on the characteristics of current cabling components. Observing from the current qualification for cabling components in [4], the product of two cross talks and the five return losses are negligible. Therefore, when modeling pair-to-pair cross-talk, other quiet pairs have insignificant influences on the cross-talk to the two pairs under study. Therefore, when modeling these two cross-talking pairs, the system under study can be simplified as a 4-port system instead of 8-port system, but the characteristics of the original 8-port system still exist in the characteristic impedance at each port. Using the above outlined simplification method, a 4-port transmission matrix is simplified and cascaded with another stage. The simplified two stage cascaded transmission matrix is transformed to a 4-port S-parameter matrix. All the simplifications of terms in matrices are done using Mathematica Version 5. The 4-port model is shown in Figure 1. The S-parameters of this 4-port model are introduced as follows. The reflection coefficient for port pp can be obtained by measuring S_{pp}, which is

$$Sn_{pp} = Sa_{pp} + \frac{Sa_{rp} Sb_{pp} Sa_{pr}}{1 - Sa_{rr} Sb_{pp}} \tag{1}$$

The transmission coefficient for port p to port q can be obtained by measuring S_{rp}, which is

$$Sn_{rp} = \frac{Sa_{rp} Sb_{rp}}{1 - Sa_{rr} Sb_{pp}} \tag{2}$$

The near end coupling coefficient can be obtained by measuring S_{pq}, which is

$$Sn_{qp} = Sa_{qp} + \frac{Sa_{rp} Sb_{pp} Sa_{qr}}{1 - Sa_{rr} Sb_{pp}} + \frac{Sa_{sp} Sb_{qq} Sa_{sq}}{1 - Sa_{ss} Sb_{qq}} + \frac{Sa_{rp} \left(Sb_{qp} + Sb_{pp} Sa_{sr} Sb_{qq}\right) Sa_{qs}}{\left(1 - Sa_{rr} Sb_{pp}\right)\left(1 - Sa_{ss} Sb_{qq}\right)} \tag{3}$$

The far end coupling coefficient can be obtained by measuring S_{sp}, which is

$$Sn_{sp} = \frac{Sa_{rp} Sb_{sp}}{1 - Sa_{rr} Sb_{pp}} + \frac{Sa_{sp} Sb_{sq}}{1 - Sa_{ss} Sb_{qq}} + \frac{Sa_{rp} \left(Sb_{pp} Sa_{sr} + Sb_{qp} Sa_{ss}\right) Sb_{sq}}{\left(1 - Sa_{rr} Sb_{pp}\right)\left(1 - Sa_{ss} Sb_{qq}\right)} \tag{4}$$

The a and b represent the first and second stages in the cascade system. However, in computation, the two cascaded results can be treated as a new stage a and the next stage can be treated as b. If only the characteristics of the worst cross-talk pairs in the cabling system are studied, then the cascaded characteristics can be obtained by apply equations (1) to (4) thorough all the stages. A multi-stage 8-port cascaded system can be analyzed applying the same procedure to all the pair-to-pair combinations. Identical equations can also be obtained by using the signal flow graph method with Mason's non-touching loop rules [5].

From this 4-port model, some important concepts can be observed that also agree with measurement experiences for cabling systems. The return loss (RL) at each port (pair) is determined primarily by the characteristic impedance at each stage and junction mismatch. The cross-talks do not significantly impact the return loss measurements. The insertion loss (IL) is only determined by the insertion loss at each stage and the junction mismatch, and the cross-talks do not have impact on insertion loss. The near end cross talk (NEXT) is determined by the NEXT at the first stage, and the NEXT at later stages are directly added to the front stage after being attenuated by the insertion loss at former stage, when junction mismatch is small. From equation (3) the relation between NEXT and far end cross talk (FEXT) are also observed. The signal reflected from the junction mismatch will be added to the NEXT through FEXT of the former stage. The far end cross talk (FEXT) is determined by the possible signal transmission paths of the far end to the near end. NEXTs are also added to the cascaded FEXT when the junction is mismatched. Therefore, the relations of the S-parameters at each stage are shown in equations (1) to (4), which may provide insights for both system and component designs.

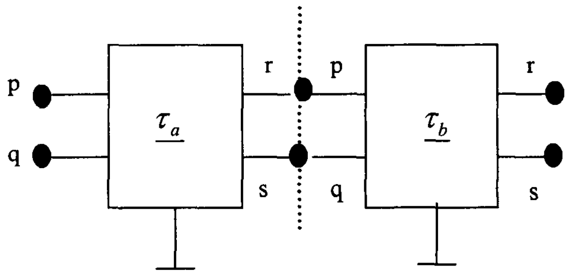

Figure 1 The 4-Port scattering parameter model.

Validations

A category 6 (CAT 6), used up to 250 MHz, telecommunication permanent link is built to verify the effectiveness of these equations. The link consists of two 2 m patch cables at each end, two connectors, and 90 m horizontal cable as shown in Figure 2. The test equipment is HP 8753 D network analyzer with 2 baluns at each port. For link testing, the patch cable ends are modified to 4 test lead pairs to connect with baluns in the network analyzer setup. The link is partially tested at the worst cross-talk pairs which are the pair of connector contact 3 and 6 and the pair of connector contacts 4 and 5. After the link testing, the system is divided into 5 individual stages, which are 2 patch cables, 2 connectors, and the horizontal cable. The individual components are measured under the same procedures. The cascade of the link performance is computed using the measurement results at each stage in equations (1) to (4). Because of the symmetry in the link, only a part of the measurement and cascaded results are shown in Figure (3) to (7). The effectiveness of these equations is proven. The slight difference in return loss between measurement and cascade results is resulted from the changes in the effective length of each cable. When measuring each stage, portions of the connecting cables are modified into test lead pairs. In this verification measurement, 12 inches of cables are modified into test leads. This change is mainly shown in the input impedance of each cable. However, for insertion losses, NEXT losses, and FEXT losses, the influences due to the changes of the effective lengths are not significant. The equations can not only accurately model the magnitude, but also the phase of the cascaded system. When evaluating digital systems, delay skew is also an important consideration. The delay skew of the system is determined by the phase change of system transmission. In Figure 6, the difference of the phase change between the link measurement results and cascaded results are not detectable. Therefore, equations (1) to (4) are very accurate and are a simplified model for current cabling system.

Conclusions

Simplified equations for a 4-port scattering parameter for cabling systems are presented and verified. These equations not only provide accurate cascade results when components are known, but also provide insights of the interactions between S-parameters at each stage. In additions, when measurements of the system and the adapter are available, the de-embedded system characteristics are also obtainable using equations (1) to (4). These equations can also be applied to multi-port systems such that the product of two cross talks and the product of five return losses are negligible.

Acknowledgements

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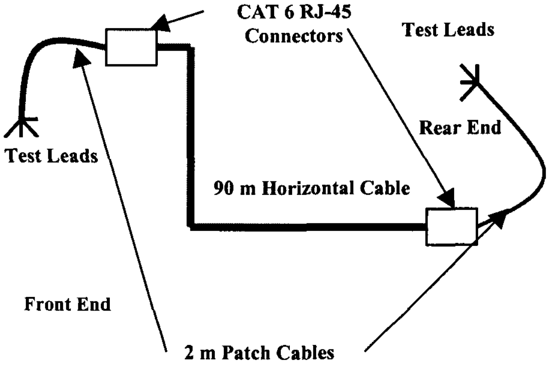

Figure 2. The device under test: a 94 m telecommunications permanent link.

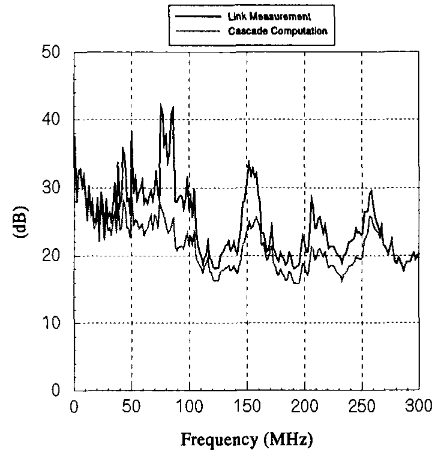

Figure 3 The return loss of the link measurements and cascade computations at the front end contacts 3 and 6.

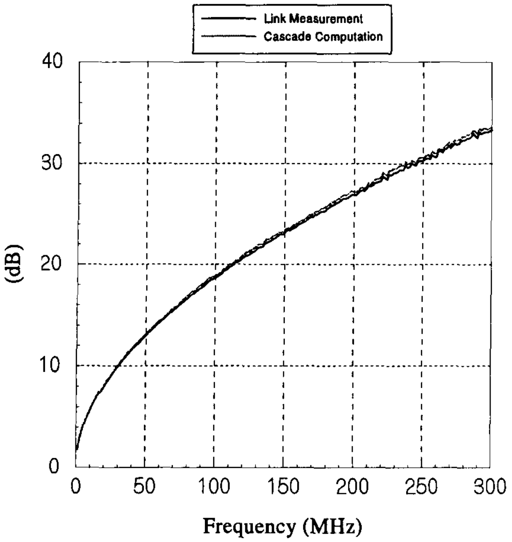

Figure 4 The insertion loss of the link measurements and cascade computations measured from the front end contacts 3 and 6 to the rear end contacts 3 and 6.

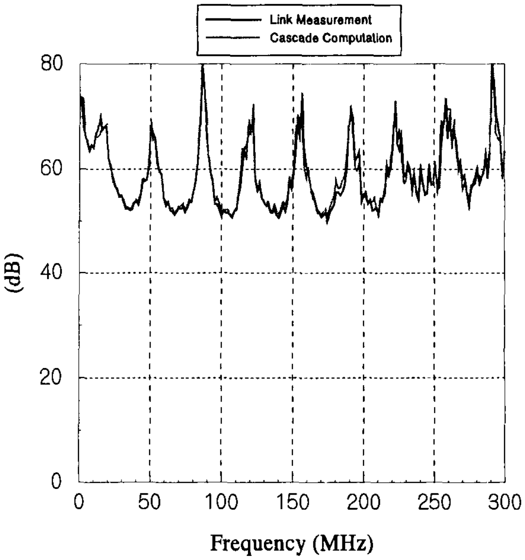

Figure 5 The far end cross talk loss of the link measurements and the cascade computations measured from the front end contacts 3 and 6 to the rear end contacts 4 and 5.

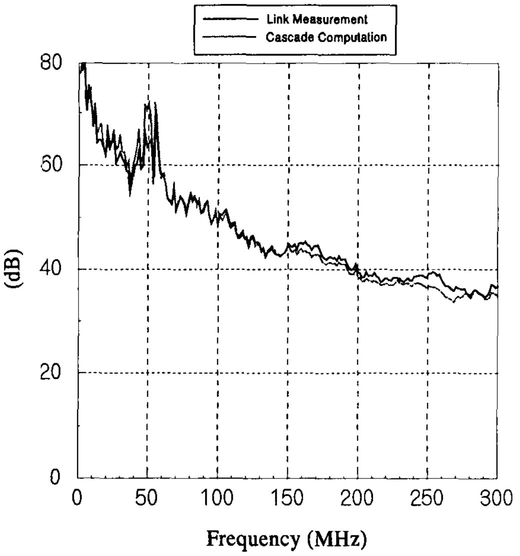

Figure 5 The near end cross talk loss of link measurements and cascade computations measured between the front end contacts 3 and 6 and contacts 4 and 5.

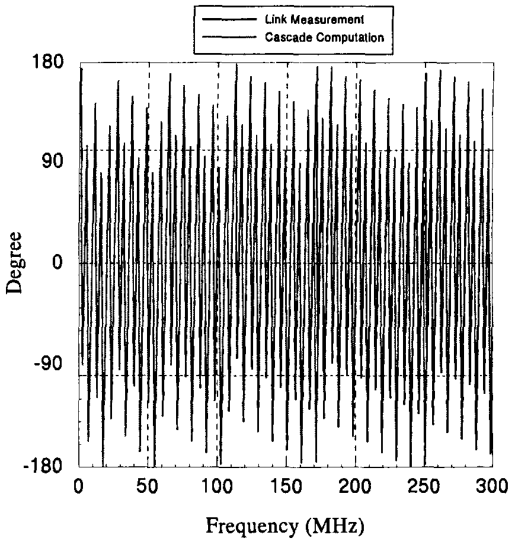

Figure 6 The transmission phase change of the link measurements and cascade computations measured from the front end contacts 3 and 6 to the rear end contacts 4 and 5.