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Abstract:
In order to make accurate reflectometry measurements on electric cables for fault diagnosis, connector de-embedding is a procedure for compensating measurement distortions caused by unmatched connectors. The key step in such a procedure is the characterization of the connectors, which is realized through measurements on a pair of connectors linked by a short cable segment. The analysis for deducing the characteristics of a single connector from measurements made on an assembled pair is known as the bisection problem. In this paper, after recalling the underdetermined nature of the bisection problem, a practically effective de-embedding procedure is proposed based on a particular regularization technique. Numerical examples are presented to illustrate the effectiveness of this procedure.

Keywords: De-embedding, bisection problem, electrical cable, fault diagnosis, reflectometry.

1. INTRODUCTION

In modern engineering systems, due to the fast development of electric and electronic devices, the number of wired connections and the total length of connecting cables have been drastically increased during the last decades. Efficient tools for cable and wired network monitoring are becoming necessary. Reflectometry is a promising non destructive technique for cable fault diagnosis (Furse et al., 2003; Smail et al., 2010; Auzanneau, 2013; Shi and Kanoun, 2014). To apply this technique, a cable under test is connected to an electronic instrument, typically a *vector network analyzer* (VNA), in order to make reflectometry measurements. The connection between the instrument and the cable is usually realized through connectors, which are often permanently mounted on the cable. As a consequence, the measurement acquired with the instrument reflects the characteristics of the set composed of the cable and its connectors, whereas the purpose of the measurement is to characterize the cable.

Significant difference in impedance between the connectors and the cable, known as *impedance mismatch*, can lead to important measurement distortions. It is thus important to develop methods for reflectometry data preprocessing in order to remove the effect of connectors from data. Such a data preprocessing is known as *de-embedding*, typically involving a sophisticated measurement calibration procedure.

If the characteristics of the connectors are known, then they can be used for connector de-embedding. However, the manufacturer's data are often incomplete or limited to a frequency band that is not sufficient for connector de-embedding in reflectometry applications. For this reason, a de-embedding procedure typically includes the characterization of the connectors.

To directly characterize a connector for the purpose of de-embedding, its both sides should be connected to two ports of an instrument, such as a VNA, to make measurements. A connector to be mounted on a cable has one of its two sides designed to crimp the cable, which cannot be reliably connected to conventional reflectometry instruments. This difficulty may be indirectly overcome through specially designed experiments.

A quite natural experiment is to use a pair of identical connectors mounted on a short cable segment, like the one illustrated in Figure 1. This assembled connector pair can be easily connected to two ports of a VNA in order to be characterized. However, the purpose is to characterize a single connector, not this assembled device. It was expected that, by analyzing the results of the assembled device, a single connector could be indirectly characterized. This analysis, known as the *bisection problem*, has already been studied in the literature (Song et al., 2001; Sekiguchi et al., 2010; Zúñiga-Juárez et al., 2012; Daniel et al., 2014).

It is well known that the bisection problem is underdetermined: by modeling a connector as a general two-port device, it is impossible to determine the characteristics of each of the two connectors from measurements on the assembled pair. Under the reciprocal assumption (Collin, 2001), a two-port device is generally characterized in the frequency domain with 3 complex valued parameters. Different methods have been proposed in the literature to solve the bisection problem, typically by assuming reduced connector models. In (Song et al., 2001; Sekiguchi et al., 2010), the bisection problem has been investigated based on Π-equivalent or T-equivalent models of an assembled connector pair, in which each connector is characterized by 2 parameters. In (Zúñiga-Juárez et al., 2012), the two sides of each single connector are assumed symmetric, and this symmetry implies a connector model of 2 parameters. By reducing the 3 parameters of a reciprocal two-port device to 2 parameters, these methods remove the underdetermination in the bisection problem, but no justification for the relevance of these reduced models has been reported, to our knowledge.

In (Daniel et al., 2014) the bisection problem is solved with an optimization algorithm. Because the bisection problem is underdetermined, the criterion to be minimized is degenerate: its minimum is reached for all the connector parameter values belonging to a manifold. The solution proposed in (Daniel et al., 2014) is the application of a particular optimization algorithm, the *Levenberg-Marquardt* algorithm, that always produces a single solution in case of degenerate optimization problem. However, there is no justification that the solution picked up by the Levenberg-Marquardt algorithm is relevant for connector de-embedding. As a matter of fact, it is not difficult to imagine other strategies for picking up a unique solution among the infinitely many solutions minimizing the considered criterion. However, it is not obvious which one is relevant.

The purpose of this paper is twofold: an analysis of the bisection problem, and a practically effective method for connector de-embedding. After the introduction, the considered bisection problem will be formulated in Section 2, the underdetermined nature of the bisection problem will be analyzed in Section 3, a regularization-based solution will then be proposed, in Section 4, before numerical examples in Section 5 and the conclusion in Section 6.

2. PROBLEM STATEMENT

In electrical engineering, a high frequency two-port *device under test* (DUT) is often characterized in frequency domain with different parameters, such as the scattering (S) parameters or the impedance (Z) parameters (Paul, 2008). For the problem considered in this paper, the most convenient form of characterization is the ABCD parameters, also known as chain, cascade or transmission parameters, as defined in the following. Let $V_1(\omega)$ and $I_1(\omega)$ be the voltage and the current at port-1 of a two-port DUT, and similarly $V_2(\omega)$ and $I_2(\omega)$ at port-2, with ω denoting the angular frequency. The signs of the two currents are as illustrated in Figure 2. The matrix of ABCD parameters, or the *ABCD matrix* for short, at the angular frequency ω, is a 2×2 matrix composed of scalar complex-valued parameters $A(\omega), B(\omega), C(\omega), D(\omega)$ such that

$$\begin{bmatrix} V_1(\omega) \\ I_1(\omega) \end{bmatrix} = \begin{bmatrix} A(\omega) & B(\omega) \\ C(\omega) & D(\omega) \end{bmatrix} \begin{bmatrix} V_2(\omega) \\ -I_2(\omega) \end{bmatrix}. \tag{1}$$

Consider a connector mounted on a cable. The connector, as a two-port component, has one side (port-1) designed for making connections with other devices, and another side (port-2) crimping one end of the cable. If the ABCD matrix of the connector is known (within a sufficiently large frequency band for the purpose of cable characterization), then it can be used for de-embedding. For example,

Fig. 1. A pair of connectors mounted on a short cable segment.

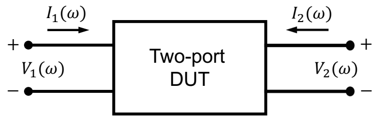

Fig. 2. A two-port device under test (DUT).

assume that the voltage $V_1(\omega)$ and the current $I_1(\omega)$ at port-1 are measured with an instrument, then the voltage $V_2(\omega)$ and the current $I_2(\omega)$ at port-2 (the side of the connector in contact with the cable) can be deduced from the measured values $V_1(\omega)$ and $I_1(\omega)$ by inverting the ABCD matrix in equation (1). The task of connector de-embedding is then fulfilled.

The ABCD matrix of a connector may be obtained from measurements. If the two sides of the connector could be directly connected to a two-port instrument, say, a VNA, then its ABCD matrix would be deduced from the measurement delivered by the VNA. Unfortunately, as one side of the connector is designed to be mounted on a cable, it cannot be *reliably* connected to conventional instruments. An adapter might be used, but then the resulting ABCD matrix would characterize the set composed of the connector and the adapter, whereas it is the connector that should be characterized!

One possible solution is to use a pair of connectors, mounted on the two ends of a short cable segment, say of length h, like the one illustrated in Figure 1. Such an assembled device can be easily connected to two ports of an VNA in order to make measurements. Instead of trying to deduce the characteristics of each of the two connectors from measurements made on the entire device, it should be easier to deduce the characteristics of each half of the device, by assuming that the two halves are symmetric. This task is known as the *bisection problem* in the literature (Song et al., 2001; Sekiguchi et al., 2010; Zúñiga-Juárez et al., 2012; Daniel et al., 2014).

Suppose that the bisection problem can be solved, then it results in the ABCD matrix of a connector and half of the short cable segment. Instead of removing the effect of the half cable segment (of length $h/2$) from the ABCD matrix, this small portion of cable can be treated as part of the connector. This practice assumes that the short cable segment has the same characteristics as the cable to be measured with identical connectors.

In what follows, for shorter notations, the angular frequency ω will be omitted from equations, unless its presence is necessary. Yet for ease of presentation, a pair of connectors mounted on a short cable segment, like the one illustrated in Figure 1, will be simply referred to as a *connector pair*, and each of its two halves, including a connector and half of the short cable segment, will be called a *half connector pair*.

Let the ABCD matrix of the *left half* of a connector pair (including the left side connector and half of the short cable segment) be denoted by

$$P = \begin{bmatrix} a & b \\ c & d \end{bmatrix}, \quad (2)$$

where a, b, c, d are complex values depending on ω, but the notation "(ω)" is omitted.

By assuming that the connector and the cable segment satisfy the *reciprocal* property [1] (Collin, 2001), the matrix P has a unitary determinant:

$$\det(P) = ad - bc = 1. \quad (3)$$

Similarly, let the ABCD matrix of the *right half* of the connector pair be denoted by Q. Due to the symmetry of the two halves and to the reciprocity assumption, Q is equal to the transpose of P along the anti-diagonal, *i.e.*,

$$Q = \begin{bmatrix} d & b \\ c & a \end{bmatrix}. \quad (4)$$

The ABCD matrix of the whole assembled device, denoted by M_0, then satisfies

$$M_0 = PQ. \quad (5)$$

The matrix M_0 can be measured by connecting the whole assembled device to a two-port VNA. The bisection problem considered in this paper, for the purpose of connector de-embedding, then consists of determining P from the measured M_0, possibly by incorporating other similar measurements $M_1, M_2, \ldots$, that will be introduced later.

3. ANALYSIS OF THE BISECTION PROBLEM

In this section, it is first recalled that the P matrix is determined by the measured M_0 up to a degree of freedom among the 4 entries a, b, c, d of P. By choosing a as the free parameter, the other parameters, namely b, c, d, are then expressed with a and M_0.

3.1 The basic bisection problem

Due to the reciprocal property (3), P and Q are invertible matrices, and the inverse of Q is

$$Q^{-1} = \begin{bmatrix} a & -b \\ -c & d \end{bmatrix}. \quad (6)$$

Rewrite equation (5) as

$$M_0 Q^{-1} = P. \quad (7)$$

Let the matrix M_0 be detailed as

$$M_0 = \begin{bmatrix} \alpha_0 & \beta_0 \\ \gamma_0 & \alpha_0 \end{bmatrix}, \quad (8)$$

where the same complex value α_0 appears at the two diagonal entries, because of the symmetry of the connector pair. Moreover, its reciprocal property implies

$$\alpha_0^2 - \beta_0\gamma_0 = 1. \quad (9)$$

Then the matrix equation (7) is detailed as

$$\begin{bmatrix} \alpha_0 & \beta_0 \\ \gamma_0 & \alpha_0 \end{bmatrix} \begin{bmatrix} a & -b \\ -c & d \end{bmatrix} = \begin{bmatrix} a & b \\ c & d \end{bmatrix}. \quad (10)$$

[1] A reciprocal device is one in which the transmission of signals between two ports does not depend on the direction of transmission. Typically a reciprocal device is built from passive and isotropic materials (Collin, 2001). In the scattering (S) parameter representation, the reciprocal property implies symmetric S matrix (not Hermitian).

This matrix equation has the advantage of being linear in the unknowns a, b, c, d, whereas the matrix equation (5) is quadratic in the same unknowns. The linear equation (10) can be rearranged as

$$\begin{bmatrix} \alpha_0 - 1 & -\beta_0 & & \\ \gamma_0 & -(\alpha_0+1) & & \\ & & \alpha_0+1 & -\beta_0 \\ & & \gamma_0 & -\alpha_0+1 \end{bmatrix} \begin{bmatrix} a \\ c \\ b \\ d \end{bmatrix} = 0 \quad (11)$$

where the omitted matrix entries are zeros. The determinant of the first diagonal block is equal to $-(\alpha_0-1)(\alpha_0+1)+\beta_0\gamma_0 = 1-\alpha_0^2+\beta_0\gamma_0 = 0$, due to (9). Similarly, the determinant of the second diagonal block is also zero. Therefore, the 4 scalar linear equations in (11) contain only *2 linearly independent equations*. These equations, together with the reciprocal condition (3), cannot completely determine the 4 unknowns a, b, c, d.

To summarize, based on the measured M_0 and the reciprocal condition, without any other information, the matrix P is determined up to 1 degree of freedom.

3.2 Connector models depending on a single free parameter

It was shown in Section 3.1 that, after the measurement M_0, there remains one degree of freedom among the entries a, b, c, d of P. Let us choose a as the free parameter in order to express the other ones. It then follows from (3) and (11) that

$$P = \begin{bmatrix} a & \dfrac{\beta_0}{2\,a} \\ \dfrac{a\,(\alpha_0-1)}{\beta_0} & \dfrac{\beta_0\,\gamma_0}{2a\,(\alpha_0-1)} \end{bmatrix} \quad (12)$$

and similarly,

$$Q = \begin{bmatrix} \dfrac{\beta_0\,\gamma_0}{2\,a\,(\alpha_0-1)} & \dfrac{\beta_0}{2\,a} \\ \dfrac{a\,(\alpha_0-1)}{\beta_0} & a \end{bmatrix}. \quad (13)$$

This result will be used in the next section for a solution of the bisection problem based on regularization.

4. DE-EMBEDDING BY REGULARIZATION

Despite the underdetermined nature of the bisection problem, a practically effective de-embedding procedure will be proposed in this section, based on a particular mode of regularization.

Regularization techniques are frequently used for solving ill-posed inverse problems (Engl et al., 2000). Typically, regularization consists in adding a penalty term to a criterion to be minimized, however, the regularization proposed below will be introduced in a different manner.

The ABCD matrix of an ideal connector is the identity matrix. A reasonably designed connector, possibly unmatched to the cable on which it is mounted, should not be too far from this ideal behavior, despite significant distortions it can introduce to measurements in case of impedance mismatch. The idea of regularization proposed here is to choose, in the connector ABCD matrix P as expressed in (12), a value of the free parameter a so that P is close to the identity matrix in some sense.

The simplest solution for such a regularization is to set $a = 1$. With this choice, the first diagonal entry of P is

$$P(\omega) = \begin{bmatrix} 1 + \dfrac{10^{-6}}{50 + 10^7/(i\omega)} & 2.5 \times 10^{-6} + \dfrac{1.5 \times 10^{-12}}{50 + 10^7/(i\omega)} \\ \dfrac{1}{50 + 10^7/(i\omega)} & 1 + \dfrac{1.5 \times 10^{-6}}{50 + 10^7/(i\omega)} \end{bmatrix}. \quad (14)$$

equal to 1, like in the identity matrix. Hopefully, the P matrix in (12) computed with $a = 1$, namely

$$P = \begin{bmatrix} 1 & \dfrac{\beta_0}{2} \\ \dfrac{(\alpha_0 - 1)}{\beta_0} & \dfrac{\beta_0 \gamma_0}{2(\alpha_0 - 1)} \end{bmatrix} \quad (15)$$

will be close to the identity matrix.

A better solution is to choose the value of a that minimizes (the square of) the Frobenius norm of the matrix $I - P(a)$:

$$\hat{a} = \arg\min_a \text{Trace}\left[(I - P(a))(I - P(a))^*\right], \quad (16)$$

where I denotes the 2×2 identity matrix, $P(a)$ represents the matrix P depending on a, and the exponent "$*$" indicates conjugate transpose. This minimization can be easily made numerically, for a local minimum close to $a = 1$.

As all the involved quantities are frequency-dependent, the computations must be repeated for every frequency.

This de-embedding method will be illustrated in the next section through a numerical example.

5. NUMERICAL EXAMPLE

The simulation configuration includes a cable of 3.02 meters (m) and two connectors mounted at the two ends of the cable. For data generation by numerical simulation, each connector and the attached 1cm cable segment ($h/2 = $ 1cm) are modeled by the frequency-dependent ABCD matrix displayed at the top of this page in equation (14) (which will be referred to as "the connector model" for shorter sentences).

The remaining cable of 3m length between the two connectors is simulated with the RLCG model. Its parameters are chosen as $R = 0.02\Omega/\text{m}$, $L = 2.47 \times 10^{-7}\text{H/m}$, $C = 9.88 \times 10^{-11}\text{F/m}$ and $G = 1 \times 10^{-9}\text{S/m}$. The RLCG parameters are uniform along the cable, but a fault corresponding to a local ohmic loss is simulated at 1.05m from the left end of the cable. This fault is equivalent to a 10Ω lumped resistance inserted in series in one of the conductors of the cable.

Frequency domain data are simulated for frequencies equally spaced between 0 and 2GHz, with a increment of 10MHz. At each of these frequencies, the ABCD matrices of the connectors and of the 3m cable are first computed separately, then their product gives the ABCD matrix of the whole simulated device.

For the purpose of de-embedding, the ABCD matrix M_0 of the two connectors mounted on a 2cm cable segment is simulated by computing the matrix product PQ.

In this example, the 10Ω lumped resistance simulates a local lossy fault. The simulated data are then used for fault diagnosis, based on an algorithm capable of estimating the resistance profile of the cable from the simulated data. See (Berrabah et al., 2016) for a detailed presentation of this algorithm.

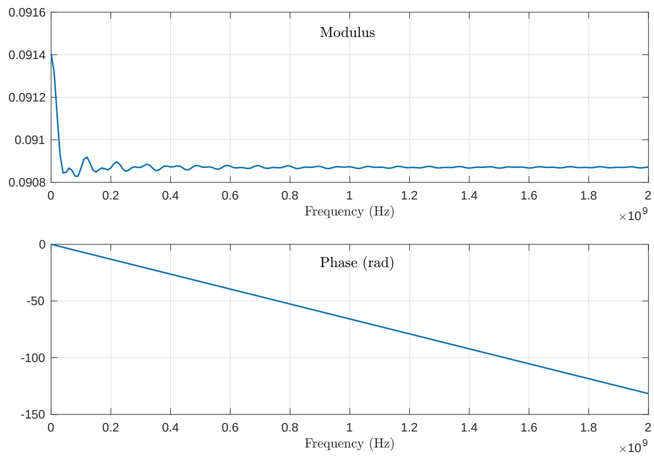

Fig. 3. $S_{11}(\omega)$ with ideal connectors mounted on the simulated cable.

As scattering (S) parameters are the most often used data format in such experiments, the simulated ABCD matrices are converted to S parameters for their visualisation.

The $S_{11}(\omega)$ parameter simulated with *ideal connectors* mounted on the simulated cable is first displayed in Figure 3. An *ideal connector* has its ABCD matrix equal to the identity matrix. Then the connector model is replaced by the ABCD matrix (14), and the resulting $S_{11}(\omega)$ parameter is plotted in Figure 4. It appears that the measurement has been considerably distorted by the unmatched connectors, since the two S_{11} parameters are very different. Nevertheless, the simulated unmatched connectors have their ABCD matrix as specified in (14) quite close to the identity matrix. For instance, the P-matrix at 0Hz, 10MHz and 100MHz are as in equations (17) displayed on the next page.

The de-embedding method by minimizing the matrix norm in (16) with the simplex search method is then applied to compensate the distortions from the simulated data. The resulting compensated $S_{11}(\omega)$ is shown in Figure 5, which is closer to the data simulated with the ideal connectors (Figure 3).

In order to further evaluate the proposed de-embedding method, let us apply the fault diagnosis algorithm presented in (Berrabah et al., 2016) to these simulated data and compare the results. The results obtained from data simulated with ideal connectors and with unmatched connectors are illustrated in Figure 6. The algorithm estimates the cable resistance profile $R(z)$. An ohmic loss fault has been simulated by inserting a lumped resistance at $z = $ 1.05m. In theory the lumped resistance leads to a Dirac function spike of $R(z)$ at $z = $ 1.05m. As the diagnosis algorithm estimates $R(z)$ from data of limited frequencies, the Dirac function is approximated by a finite spike in each estimated $R(z)$ profile. The lumped resistance inserted in the cable is then estimated by integrating the spike of the

$$P(0\text{Hz}) = \begin{bmatrix} 1 & 2.5 \times 10^{-6} \\ 0 & 1 \end{bmatrix} \tag{17a}$$

$$P(10\text{MHz}) = \begin{bmatrix} 1 + i6.3661 \times 10^{-11} & 2.5 \times 10^{-6} + i9.5492 \times 10^{-17} \\ 0.02 + 6.3661 \times 10^{-5} & 1 + i9.5492 \times 10^{-11} \end{bmatrix} \tag{17b}$$

$$P(100\text{MHz}) = \begin{bmatrix} 1 + i6.3662 \times 10^{-12} & 2.5 \times 10^{-6} + i9.5493 \times 10^{-18} \\ 0.02 + 6.3662 \times 10^{-6} & 1 + i9.5493 \times 10^{-12} \end{bmatrix}. \tag{17c}$$

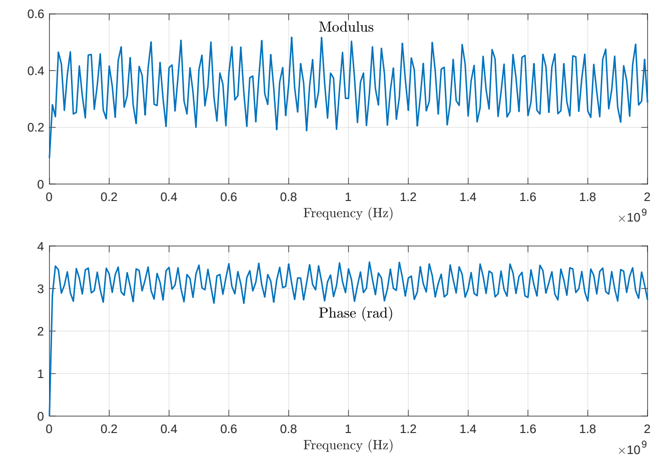

Fig. 4. $S_{11}(\omega)$ with unmatched connectors (simulated with the P-matrix (14)) mounted on the simulated cable.

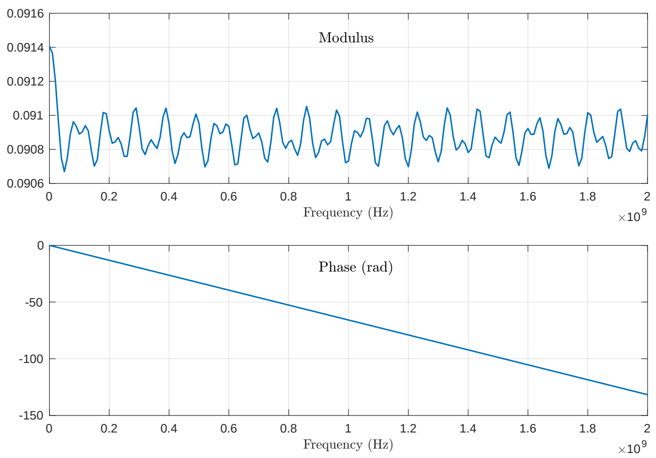

Fig. 5. $S_{11}(\omega)$ after de-embedding.

estimated $R(z)$ profile. In Figure 6, the estimated lumped resistance from data with ideal connectors is 10.018Ω, whereas the estimate resulting from data with unmatched connectors is 5.327Ω, which is much farther away from the true simulated resistance of 10Ω. The effect of data distortion by the unmatched connectors is thus significant.

The fault diagnosis algorithm is then applied to the data after de-embedding. The result is presented in Figures 7. The estimated resistance profile $R(z)$ is similar to the profile estimated from data simulated with ideal connectors (the blue curve in Figure 6), and the estimated lumped resistance value of 10.021Ω is quite close to the true simulated resistance R=10Ω, confirming the effectiveness of the de-embedding procedure.

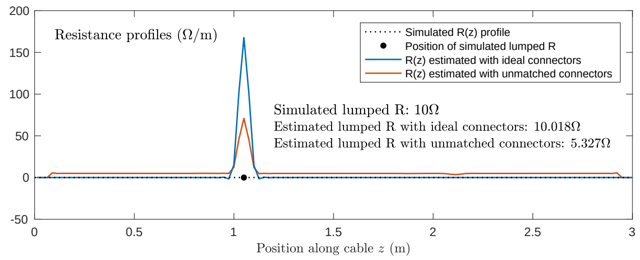

Fig. 6. Simulated cable resistance profile $R(z)$ (uniform except a lumped R=10Ω at $z = 1.05$m), and estimated $R(z)$ with data simulated with ideal connectors or with unmatched connectors.

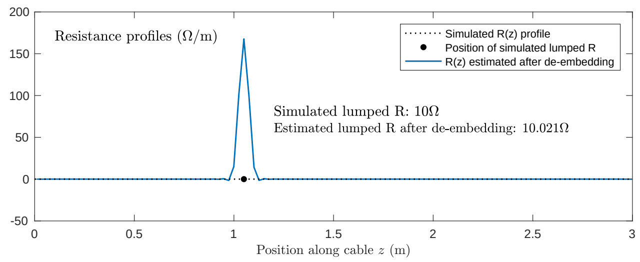

Fig. 7. Simulated cable resistance profile $R(z)$ (uniform except a lumped R=10Ω at $z = 1.05$m), and estimated $R(z)$ after de-embedding.

6. CONCLUSION

After recalling the underdetermined nature of the bisection problem for connector de-embedding, a connector model depending on a single free parameter is derived. A particular regularization technique is then proposed, based on the fact that the ABCD matrix of a good connector should be close to the identity matrix, resulting in an effective de-embedding procedure. Numerical examples have been presented in order to illustrate the proposed method. The robustness of this method to measurement errors will be investigated in future studies.

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