Binder Identification by Means of Phantom Measurements

Carine Neus, Wim Foubert, Leo Van Biesen, Yves Rolain, Patrick Boets, and Jochen Maes

Abstract—This paper presents a technique to identify if two twisted pairs (TPs) share the same binder or not, based on single-ended line measurements. If the TPs share the binder only over a certain distance, this length is determined. We first show the challenges of achieving binder identification under normal differential operation. Next, we propose an alternative by measuring two TPs simultaneously in phantom mode. The proposed approach is validated by laboratory measurements.

Index Terms—Binder identification, digital subscriber line (DSL), phantom mode (PM), scattering parameters, single-ended line testing.

I. INTRODUCTION

The twisted pairs (TPs) of a telephone network are grouped into binders, e.g., 20 pairs or more can be grouped in one binder [1]. When several digital subscriber line (DSL) services with overlapping frequency bands operate on these TPs, the presence of crosstalk will limit the total performance. This is particularly an issue for the latest xDSL technologies (e.g., VDSL2) as they use wider spectral bands [2]. For this reason, dynamic spectrum management proposes to coordinate the signals traveling on the different lines in an intelligent way [3]–[5]. However, this technique requires that the operators know which TPs are situated in the same binder.

Knowledge about the binder network is also useful for diagnosis purposes, e.g., if a fault is detected on one TP, it might be worth testing the other TPs in the same binder as well. Moreover, binder diagnosis will produce more reliable results than separate line diagnosis.

In this paper, we present a technique to identify if two TPs are located in the same binder or not. As the TPs may share the same binder for a certain distance only, the method is also extended to find the distance over which they coexist. The implementation of an automated algorithm is left for future work; instead, the emphasis is put on the measurement setup and the proof of concept, as such opening the way to many applications based on the use of binder-related information.

We have chosen to perform single-ended measurements in a controlled laboratory environment with a vector network analyzer (VNA) that is extended with a reflection test set, for the following reasons. Firstly, to allow automated binder identification, all measurements should be performed from the central office without operator interaction at the customer premises. Thus, only single-ended line measurements are adequate. In the final implementation, the aim is to implement this functionality into the xDSL modems, which are equipped with the standardized single-ended line testing capability [6]. The implementation of the presented method in xDSL models falls outside the scope of this paper. Secondly, measurements have been performed in a cable farm as it allows accurately controlling the measurement environment. Finally, the reflective time-domain response of the lines is not measured with time-domain reflectometry (TDR) but with measurements of the one-port scattering parameter with the reflection test set of a VNA. This allows calibrating the measurements and obtaining state-of-the-art accuracy levels. Simply performing an inverse fast Fourier transform on the measured one-port scattering parameter yields the reflective time-domain response, as one would obtain with TDR [7]. The time-domain responses are shown in logarithmic scale in this paper to emphasize the presence of small reflections.

The initial idea used here is that TPs in the same binder will contain similar features in their reflective time-domain responses, as they experience the same, or a very similar, influence of the environment. The correlation of the time responses of these TPs (or any other measure of similarity) is an indicator for the coexistence of the TPs within one binder [2]. This approach, although promising, is sensitive to the quality of the single-ended line measurements. It is elaborated in Section II. Therefore, an alternative approach is proposed in Section III. This latter is no longer based on the “normal” differential operation of one TP but rather measures the propagation in phantom mode (PM) between two TPs. As will be shown by measurements, this method holds great potential for binder identification. The future work is discussed in Section IV.

II. PAIRWISE DIFFERENTIAL MEASUREMENTS

A straightforward approach to binder identification extracts binder information from the measured time-domain responses of different TPs in their normal operation mode, i.e., the differential one, and analyzes them to detect similarities. The one-port scattering parameters of individual TPs have been measured with an HP 4195A VNA on an ADSL grid. As shown
Fig. 1. Measurement setup for pairwise differential operation.

Fig. 2. When $S_{11}$ is not expressed in the characteristic impedance of the line under test, several reflections are visible in the measured time-domain response before the reflection due to the end of the line.

in Fig. 1, the VNA is connected to the TP under test through the following:

1) a reflection test set (HP 41952A);
2) a North Hills balun converting the unbalanced signal from the VNA to a balanced differential signal for the TP;
3) a short TP with a Krone connector at the end, to allow easy connection to the cable rack.

For a single TP, we expect to receive a single reflection in the time-domain response due to the mismatch at the line end. However, several reflections can be seen earlier on the line, as shown in Fig. 2 for a measured 1000-m line (only consider the thin full line for the moment). The line under test was a France Telecom (FT) line with a conductor diameter of 0.4 mm (FT4). The following number indicates which binder was connected (binder 1 in this case), followed by the pair number (p3). The first additional reflection (at $t = 0$ μs) is called the near-end reflection and originates from the fact that the measurement device is not matched to the characteristic impedance $Z_c$ of the TP under test \[7, 8\]. Several subsequent reflections (at $t = 1.8$ μs, $t = 3.4$ μs, $t = 5$ μs, and $t = 6.3$ μs) are also visible, although they are not predicted by the transmission line theory.

The basic assumptions used in this theory are as follows.

1) The TP is uniform over the whole cable length.
2) The TP is a symmetrical two-port system.
3) The TP has a characteristic impedance $Z_c$ which is monotonically decaying with frequency.
4) The TP has a characteristic impedance $Z_c$ which is uniquely defined by the cable type and thus equal for all TPs of the same type.

However, in practice, these assumptions are not really valid. As can be seen in Fig. 3, a TP line is not a symmetrical two-port system, as measuring it in one direction and in the opposite direction yields different results. Measurements of the characteristic impedance (shown in Fig. 4) indicate that $Z_c$ is not monotonically decaying with frequency and that different pairs (even within the same binder) have different characteristic impedances. This strong variation between pairs was already noticed in earlier papers, e.g., in \[9\] and \[10\].

The nonuniformity of the TP was not tested, but it is known to exist and is mentioned in several papers \[11\]–\[14\]. It can be attributed to imperfections in the manufacturing, the dense packing of TPs inside binders, twist-rate variations over the cable length, and position errors of TPs within a binder.

Due to the presence of these nonidealities, the time-domain response does show not only one reflection at the line end, as the theory predicts, but also several reflections earlier on the line. What is even worse is that these reflections will differ.
from pair to pair, even within the same binder. The fact that the intermediate reflections are specific to the TP under test can be evidenced as follows.

Scattering parameters are always expressed in some reference impedance $Z_{\text{ref}}$. This impedance is most often chosen to be frequency independent, e.g., the impedance of the measurement device or the used calibration load. However, this reference impedance can be changed by postprocessing using (1)\[8\]. The renormalized scattering parameter $S_{11,\text{new}}$ corresponds to the one-port scattering parameter that one would measure with an instrument that presents an impedance $Z_{\text{new}}$.

$$S_{11,\text{new}} = \frac{Z_{\text{ref}} \left( \frac{1 + S_{11,\text{meas}}}{1 - S_{11,\text{meas}}} \right) - Z_{\text{new}}}{Z_{\text{ref}} \left( \frac{1 + S_{11,\text{meas}}}{1 - S_{11,\text{meas}}} \right) + Z_{\text{new}}}$$

When the reference impedance is changed to match the characteristic impedance of the TP under consideration ($Z_{\text{new}} = Z_c$), the near-end reflection vanishes. The measurement device is now said to be matched to the TP under test. Another interesting property of this transformation is that the intermediate reflections are reduced to the noise floor (see the thick line in Fig. 2). In contrast, changing the reference impedance to the characteristic impedance of another TP (even in the same binder) or a general impedance (a mean value or a model) does not remove the intermediate reflections (dotted and gray lines in Fig. 2). Since measuring the characteristic impedance of each TP is not feasible on a large scale and as it is conflicting with the single-ended line principle, the removal of these intermediate reflections is not envisaged.

In summary, more reflections are observed in the measurements than what is described by the models. These reflections are due to the specific characteristics of the measured TP. Any binder identification method based on similarities of the individual TP responses (e.g., [2]) should be able to make a distinction between these individual TP characteristics and reflections originating from the environment (e.g., due to splices or cross-connects). Otherwise, using similarities in the time-domain responses of two TPs could lead to erroneous results, as shown in Fig. 5. In this example, the responses of two TPs have been measured (pair 3 of binder 1 and pair 4 of binder 3) and compared to the response of a reference line (pair 2 of binder 3). The three TPs have a length of 1000 m and were left open ended. Although pair 3 of binder 1 is not situated in the same binder as the reference line, their time-domain responses show much more similarities with the reference line than TP 2, although TP 2 is situated in the same binder as the reference line, while TP 1 is not.

In the next section, we propose a different approach for binder identification that circumvents this difficulty.

III. PHANTOM MEASUREMENTS

A. Introduction

As described in the previous section, using pairwise differential measurements for binder identification is demanding, as the time-domain response highly incorporates the features of the individual TP. Therefore, an alternative is now proposed, which was found to produce promising results. Instead of measuring differentially between the two wires of one TP, we measure differentially between one pair (which has both wires shorted, hence at the same voltage) and another pair (which also has both wires shorted, i.e., at the same voltage, but with inverse sign compared to the first TP). This differential measurement setup over two TPs is called “phantom mode (PM).” This term has been used in the past for telephone quads [15], [16] and very large scale integration systems [17]. A strong advantage of using the second TP for the return path is that no ground or sheath is needed, in contrast to common-mode operation [18].

B. Measurement Setup

To allow for phantom measurements, the measurement setup was altered, as shown in Fig. 6. The differential voltage at the differential balun’s output is no longer applied to a single TP. Instead, the positive voltage is applied on both wires of one TP, and the negative voltage is applied on both wires of another TP by means of longitudinal baluns. Both TPs are left open at the line end. The measurement frequency grid is left unaltered.

This measurement setup generates a current to flow into one TP and to return through the other one. As both line ends are open, the signal can only form a closed path through capacitive coupling and inductive coupling between the two TPs. One can intuitively consent that the distance between the two TPs will strongly affect the coupling.

1) When the two TPs share the same binder, a strong coupling exists.
2) When the two TPs are located in different binders, the coupling will be much weaker.
C. Model

The transmission channel that is formed by the excitation of the two TPs connected in PM is considered as a transmission line. As all TPs have a fixed position within the binder, the line is assumed to be uniform in its longitudinal direction (the same cross section at any point of the line). Hence, a lumped circuit equivalent can be used, where a line section of infinitesimal length is described by the per-unit-length parameters: $R$ (resistance), $L$ (inductance), $G$ (conductance), and $C$ (capacitance). The characteristic impedance for the PM is given by

$$Z_{PM}^c = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \tag{2}$$

with $\omega = 2\pi f$ being the angular frequency and $j$ being the imaginary unit. Each conductor is surrounded by a circular dielectric insulation, and the wires are densely packed in a binder. Depending on the construction of the cable, the interspaces between the dielectrics are filled with air or jelly. Hence, the binder medium is inhomogeneous. Unfortunately, analytical expressions for the per-unit-length parameters $R$, $L$, $G$, and $C$ cannot be found for inhomogeneous multiconductor transmission lines, and one must resort to numerical solutions [19], [20].

In this paper, we are interested in the evolution of $Z_{PM}^c$ as a function of the separation distance $D$ between the two TPs. The conductor losses $R$ are independent of $D$, as both the copper resistance and the skin effect are only functions of the conductor material and diameter, and the proximity effect can be safely ignored as soon as the separation distance is larger than twice the wire diameter [16], [20]. The dielectric conductance $G$ depends on the dielectric thickness and will therefore decrease with increasing $D$. However, for practical lines, this contribution will be negligible compared to $j\omega C$.

As mentioned in [21] and [22], ignoring the dielectric insulation and considering the medium as homogeneous changes the capacitance values only slightly. This assumption is realistic for telephone binders as the interspaces are small, and the permittivity of the gel is close to the one of the insulation material. The capacitive coupling $C$ has been approximated numerically as described in [19], and verified with a field simulator (Ansoft Maxwell). If only the two excited TPs are considered in a homogeneous medium (polyethylene), the capacitive coupling $C$ was found to be inversely proportional to $\sqrt{D}$. The inductive coupling $L$ is related to the capacitive coupling $C$ through the magnetic permeability $\mu$ and the dielectric permittivity $\varepsilon$ of the medium ($LC = \mu\varepsilon$), [22]; hence, $L$ evolves proportionally to $\sqrt{D}$. Due to the slight inhomogeneity of the dielectric insulation, the capacitive coupling and inductive coupling will still decrease and increase with the separation distance $D$, respectively, although another law might be followed than $\sqrt{D}$.

In summary, although an analytical expression for $Z_{PM}^c$ as a function of the separation distance $D$ between the two TPs cannot be found, the combined effect of the distance $D$ on $R$, $L$, $G$, and $C$ will cause $Z_{PM}^c$ to increase with increasing distance. Hence, the theory predicts that two TPs in different binders will have a higher characteristic impedance than two TPs in the same binder. This has been verified by laboratory measurements. The characteristic impedance in PM ($Z_{PM}^c$) was calculated through an open and a short measurement [23]. The following two scenarios were considered.

a) “Same binder” scenario (Fig. 9): Two TPs share the same binder over the complete line length. The direct path is formed by the two wires of pair $N_X$ in binder $X$, and the return path is created by pair $M_X$ in the same binder $X$.

b) “Different binder” scenario (Fig. 8): Two TPs are located in different binders over the complete line length. The direct path is formed by the two wires of pair $N_X$ in binder $X$, and the return path is created by pair $M_Y$ in another binder $Y$.

Fig. 7 shows the results for three cable types: France Telecom (FT) cables with conductor diameters of 0.4 and 0.6 mm and a British Telecom (BT) cable with a conductor diameter of 0.5 mm. It confirms that the characteristic impedance in PM is indeed larger when the two TPs are situated in different binders. The difference is particularly pronounced at lower frequencies (< 500 kHz). Therefore, it can be interesting to use only the low-frequency information for binder identification purposes. We also note that, similar to the characteristic impedance in pairwise differential mode, the characteristic impedance in PM is not monotonically decaying.

D. Binder Identification

As described earlier, two TPs in different binders (Fig. 8) will have a high characteristic impedance. This will create a strong mismatch with the (lower) impedance of the measurement device. By consequence, a strong near-end reflection will be visible in the time-domain response. Moreover, as most energy is already reflected at this point, only a small portion will travel along the line and contribute to the reflection from the line end. In contrast, when the two TPs are situated in the same binder (Fig. 9), the characteristic impedance is small.
Fig. 8. Two TPs located in different binders over the complete line length ("different binder" scenario).

Fig. 9. Two TPs sharing the same binder over the complete line length ("same binder" scenario).

Fig. 10. (Dashed line) For two TPs in the same binder, the end reflection is visible in the measured time-domain response; (full line) for two TPs in different binders, the end reflection does not stand out.

Hence, the mismatch at the measurement device will be small, and most energy will be inserted onto the line. As the signal travels along the line, standing waves will be created in the frequency domain. At the encounter with the open line end, a strong reflection will occur in the time-domain response. These completely different behaviors will allow us to identify whether the two TPs are situated in the same binder or not.

These expectations have been verified by laboratory measurements. The two setups in Fig. 8 ("different binder" scenario) and Fig. 9 ("same binder" scenario) have been constructed with FT lines of 1000 m. Fig. 10 shows the time-domain responses. As expected, when the TPs are situated in the same binder, the near-end reflection (at \( t = 0 \mu s \)) is smaller than that for TPs in different binders, and the reflection from the line end (at \( t = 10 \mu s \)) stands out more clearly with respect to the intermediate reflections.

Fig. 11 shows the measured one-port scattering parameter in the frequency domain. As expected, \( |S_{11}^{PM}| \) is much higher when the two TPs are situated in different binders. Remember that the one-port scattering parameter is defined as the ratio of the reflected wave to the incident wave. Hence, a high magnitude means that a large part of the signal is reflected. Moreover, for TPs in different binders, no clear periodicity is present in the measurement. This is in contrast with the "same binder" scenario, which shows standing waves with a periodicity related to the line length.

The influence of the line length is detailed in Fig. 12 for the "same binder" scenario. The shorter the line, the higher the magnitude of \( S_{11}^{PM} \), and the larger its periodicity.

The aforementioned measurements (Figs. 10 and 11) show that it is possible to make a distinction between TPs in the same...
binder and TPs in different binders by analyzing the phantom measurements in the time or frequency domain. However, a telephone subscriber loop rarely consists of a single line connecting the central office to the customer. Therefore, it is possible that two TPs run along for a certain time and then split up. In that case, the phantom measurements also offer the possibility to determine the position where the TPs split. The following two supplementary scenarios are considered to cover these cases.

c) “Fully common” scenario (Fig. 13): Two TPs lie together in a first binder and together in a subsequent binder. The direct path is formed by the two wires of pair $N_X$ in binder $X$ in cascade with the two wires of pair $N_Y$ in binder $Y$. The return path is created by the two wires of pair $M_Y$ in binder $Y$ in cascade with the two wires of pair $M_X$ in binder $X$.

d) “Partly common” scenario (Fig. 14): Two TPs first share a common binder and then split up into different binders. The direct path is formed by the two wires of pair $N_X$ in binder $X$ in cascade with the two wires of pair $N_Y$ in binder $Y$. The return path is created by the two wires of pair $M_Z$ in a third binder $Z$ in cascade with the two wires of pair $M_X$ in the common binder $X$.

In the “fully common” scenario (Fig. 13), the characteristic impedance will be in the same order of magnitude in the first binder $X$ and in the subsequent binder $Y$. Hence, only a small reflection will occur at this junction. As in the “same binder” case (scenario a), a strong reflection will occur at the open line end. In contrast, for the “partly common” scenario (Fig. 14), the characteristic impedance will suddenly increase when transferring from the common binder $X$ (low impedance) to the different binders $Y$ and $Z$ (high impedance). Hence, a strong reflection will be created at the junction. Most of the energy will already be reflected here, and as in the “different binder” case (scenario b), a low reflection will occur at the end of the line.

These expectations have been verified by laboratory measurements, where all TPs had a line length of 1000 m. We also measured binder $X$ without any second line connected for comparison. The obtained time-domain responses are shown in Fig. 15. As expected, when the TPs split (thin gray line), a strong reflection is created at $t = 10 \mu s$ (the junction), while the end reflection (at $t = 20 \mu s$) is not visible. The reflection at the junction is almost as large as that when no second line segment was connected after binder $X$ (bulleted line). This means that the “partly common” scenario behaves as if no second binder ($Y/Z$) is connected. In contrast, when the TPs continue in a second common binder (thick gray line), only a small reflection is created at the junction, and the end reflection is clearly visible despite the total distance of 2000 m.

Similar conclusions can be drawn from the one-port scattering parameter shown in Fig. 16. When the TPs split (thin lines), the one-port scattering parameter shows standing waves with a large periodicity, corresponding to the line length of binder $X$. Moreover, the measured curves are almost independent of the type of cable that is connected after binder $X$. The one-port scattering parameter behaves as if there was no second line segment (compare with the “open” case). In contrast, for the “fully common” scenario (thick lines), the one-port scattering parameter has a lower periodicity, corresponding to the increased total length of binder $X + Y$. Hence, if the TPs coexist in the same binder only over a certain distance, an analysis of the phantom measurements in the time or frequency domain can be used to determine the distance where the TPs split.

E. Discussion

The presented results open the way for binder identification, by analysis of phantom measurements in the time-domain response or the one-port scattering parameter. The exact implementation is not in the scope of this paper; however, some ideas of possible implementation are given in the following. The information from these phantom measurements can, of course, be combined with other information, e.g., a priori information or information from pairwise differential measurements.
1) If a reflection is found in the time-domain response which corresponds to the one of an open end, then one can conclude that the two cables coexist up to this distance.

2) If the periodic behavior is absent in the frequency-domain representation of the one-port scattering parameter, then the two TPs are situated in different binders.

3) Pairwise differential measurement can be used to identify the lengths of the individual pairs. Next, one can check with phantom measurements if the end reflection is clearly visible. If yes, the TPs coexist over the complete length. If not, this means that most of the energy was lost earlier on the line. The presence of a strong reflection before the end reflection indicates the distance at which the TPs split.

The influence of the chosen pairs was also investigated. For this, one pair (acting as the forward path) was kept fixed, and the return pair was varied over the binder. If the TPs are situated in different binders, the choice of the return pair has almost no influence on the measurement (see Fig. 17). In contrast, when the TPs are situated in the same binder, the geometry of the binder comes into play (see Fig. 18). First, the capacitive coupling will slightly vary as a function of the relative position of the two considered TPs within the cable binder. Moreover, interposed TPs in the binder may act as an electric screen, as such lowering the capacitive coupling between the two TPs under consideration [24]. Nevertheless, the coupling between two nonadjacent TPs within one binder is expected to still be significantly higher than the coupling between two TPs in different binders for the following reasons: 1) The dielectric inside the binder (e.g., polyethylene) has a higher electric permittivity than air, which is the medium between different binders; hence, the electric fields will preferably stay within one binder; 2) binders are often shielded (e.g., with aluminum), as such further lowering the capacitive coupling between different binders.

When developing an algorithm for binder identification based on phantom measurements, one must first make a statistical study of the variance of $Z_{PM}$ within one binder for the considered cable type. This will allow gaining knowledge about which variations can be considered to be normal and hence defining a threshold whereupon to base the decision criterion about the location of the TPs.

### IV. Conclusion and Future Work

In this paper, we have shown that binder identification based on pairwise differential measurements is challenging because the measurements are sensitive to the nonuniformities along the TP. We have proposed a new measurement setup to measure differentially between two TPs (PM), which permitted us to identify whether two TPs were in the same binder or not. If they were only partly in the same binder, the distance at which they
split could be identified as well. The obtained results present a proof of concept, which open the way for binder identification applications with phantom measurements. The next steps are as follows: 1) to verify the results in the field (e.g., on binders with a higher number of TPs); 2) to develop an algorithm for automatic binder identification (taking the variance of the measurements into account); and 3) to adapt the modems for phantom measurements (simultaneous measurements of two TPs are needed).

REFERENCES

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Prof. Van Biesen was the President of the International Measurement Confederation (IMEKO) until September 2006. He is also a member of the board of the European Telecommunication Engineers Federation (FITCE) Belgium and the International Scientific Radio Union (URSI) Belgium. He was the Chairman of IMEKO TC-7 from 1994 to 2000, the President-Elect of IMEKO for the period 2000–2003, and the Liaison Officer between the IEEE and IMEKO.

Yves Rolain received the M.Sc. degree in electrical engineering, the M.Sc. degree in computer sciences, and the Ph.D. degree in applied sciences from Vrije Universiteit Brussel (VUB), Brussels, Belgium, in 1984, 1986, and 1993, respectively.

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In 1987, he joined the Department of Fundamental Electricity and Instrumentation (ELEC), VUB, as an Assistant and later on as a Ph.D. Assistant. At ELEC, he carried out research in the field of modeling of access network cables, data transmission, parameter estimation, and computer-controlled measurement systems. In 2007, he was a Private Consultant on WiMAX transmission and metallic transmission lines. Since 2008, he has been with Alcatel-Lucent, Antwerp, Belgium, where he was involved with research on physical layers and is currently a DSL Physical Layer Consultant.

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He is currently with Bell Laboratories, Alcatel-Lucent, Antwerp, Belgium, where he is the Team Leader for next-generation broadband projects. His research interests include nanostructured lasers, high-magnetic-field physics, digital communication, and statistics.
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1) a reflection test set (HP 41952A);
2) a North Hills balun converting the unbalanced signal from the VNA to a balanced differential signal for the TP;
3) a short TP with a Krone connector at the end, to allow easy connection to the cable rack.

For a single TP, we expect to receive a single reflection in the time-domain response due to the mismatch at the line end. However, several reflections can be seen earlier on the line, as shown in Fig. 2 for a measured 1000-m line (only consider the thin full line for the moment). The line under test was a France Telecom (FT) line with a conductor diameter of 0.4 mm (FT4). The following number indicates which binder was connected (binder 1 in this case), followed by the pair number (p3). The first additional reflection (at $t = 0 \mu s$) is called the near-end reflection and originates from the fact that the measurement device is not matched to the characteristic impedance $Z_c$ of the TP under test [7], [8]. Several subsequent reflections (at $t = 1.8 \mu s$, $t = 3.4 \mu s$, $t = 5 \mu s$, and $t = 6.3 \mu s$) are also visible, although they are not predicted by the transmission line theory.

The basic assumptions used in this theory are as follows.

1) The TP is uniform over the whole cable length.
2) The TP is a symmetrical two-port system.
3) The TP has a characteristic impedance $Z_c$ which is monotonically decaying with frequency.
4) The TP has a characteristic impedance $Z_c$ which is uniquely defined by the cable type and thus equal for all TPs of the same type.

However, in practice, these assumptions are not really valid. As can be seen in Fig. 3, a TP line is not a symmetrical two-port system, as measuring it in one direction and in the opposite direction yields different results. Measurements of the characteristic impedance (shown in Fig. 4) indicate that $Z_c$ is not monotonically decaying with frequency and that different pairs (even within the same binder) have different characteristic impedances. This strong variation between pairs was already noticed in earlier papers, e.g., in [9] and [10].

The nonuniformity of the TP was not tested, but it is known to exist and is mentioned in several papers [11]–[14]. It can be attributed to imperfections in the manufacturing, the dense packing of TPs inside binders, twist-rate variations over the cable length, and position errors of TPs within a binder.

Due to the presence of these nonidealities, the time-domain response does show not only one reflection at the line end, as the theory predicts, but also several reflections earlier on the line. What is even worse is that these reflections will differ
from pair to pair, even within the same binder. The fact that the intermediate reflections are specific to the TP under test can be evidenced as follows.

Scattering parameters are always expressed in some reference impedance $Z_{\text{ref}}$. This impedance is most often chosen to be frequency independent, e.g., the impedance of the measurement device or the used calibration load. However, this reference impedance can be changed by postprocessing using (1) [8]. The renormalized scattering parameter $S_{11,\text{new}}$ corresponds to the one-port scattering parameter that one would measure with an instrument that presents an impedance $Z_{\text{new}}$.

$$S_{11,\text{new}} = \frac{Z_{\text{ref}} \left( 1 + S_{11,\text{meas}} \right)}{1 - S_{11,\text{meas}}} - Z_{\text{new}} = Z_{\text{ref}} \left( 1 + S_{11,\text{meas}} \right) + Z_{\text{new}}.$$

When the reference impedance is changed to match the characteristic impedance of the TP under consideration ($Z_{\text{new}} = Z_c$), the near-end reflection vanishes. The measurement device is now said to be matched to the TP under test. Another interesting property of this transformation is that the intermediate reflections are reduced to the noise floor (see the thick line in Fig. 2). In contrast, changing the reference impedance to the characteristic impedance of another TP (even in the same binder) or a general impedance (a mean value or a model) does not remove the intermediate reflections (dotted and gray lines in Fig. 2). Since measuring the characteristic impedance of each TP is not feasible on a large scale and as it is conflicting with the single-ended line principle, the removal of these intermediate reflections is not envisaged.

In summary, more reflections are observed in the measurements than what is described by the models. These reflections are due to the specific characteristics of the measured TP. Any binder identification method based on similarities of the individual TP responses (e.g., [2]) should be able to make a distinction between these individual TP characteristics and reflections originating from the environment (e.g., due to splices or cross-connects). Otherwise, using similarities in the time-domain responses of two TPs could lead to erroneous results, as shown in Fig. 5. In this example, the responses of two TPs have been measured (pair 3 of binder 1 and pair 4 of binder 3) and compared to the response of a reference line (pair 2 of binder 3). The three TPs have a length of 1000 m and were left open ended. Although pair 3 of binder 1 is not situated in the same binder as the reference line, their time-domain responses show a quite similar behavior up to $t = 10 \mu s$ (the reflection from the line end). In contrast, pair 4 of binder 3, which is situated in the same binder as the reference line, shows less similarities.

In the next section, we propose a different approach for binder identification that circumvents this difficulty.

III. PHANTOM MEASUREMENTS

A. Introduction

As described in the previous section, using pairwise differential measurements for binder identification is demanding, as the time-domain response highly incorporates the features of the individual TP. Therefore, an alternative is now proposed, which was found to produce promising results. Instead of measuring differentially between the two wires of one TP, we measure differentially between one pair (which has both wires shorted, hence at the same voltage) and another pair (which also has both wires shorted, i.e., at the same voltage, but with inverse sign compared to the first TP). This differential measurement setup over two TPs is called “phantom mode (PM).” This term has been used in the past for telephone quads [15], [16] and very large scale integration systems [17]. A strong advantage of using the second TP for the return path is that no ground or sheath is needed, in contrast to common-mode operation [18].

B. Measurement Setup

To allow for phantom measurements, the measurement setup was altered, as shown in Fig. 6. The differential voltage at the differential balun’s output is no longer applied to a single TP. Instead, the positive voltage is applied on both wires of one TP, and the negative voltage is applied on both wires of another TP by means of longitudinal baluns. Both TPs are left open at the line end. The measurement frequency grid is left unaltered.

This measurement setup generates a current to flow into one TP and to return through the other one. As both line ends are open, the signal can only form a closed path through capacitive coupling and inductive coupling between the two TPs. One can intuitively consent that the distance between the two TPs will strongly affect the coupling.

1) When the two TPs share the same binder, a strong coupling exists.
2) When the two TPs are located in different binders, the coupling will be much weaker.
C. Model

The transmission channel that is formed by the excitation of the two TPs connected in PM is considered as a transmission line. As all TPs have a fixed position within the binder, the line is assumed to be uniform in its longitudinal direction (the same cross section at any point of the line). Hence, a lumped circuit equivalent can be used, where a line section of infinitesimal length is described by the per-unit-length parameters: \( R \) (resistance), \( L \) (inductance), \( G \) (conductance), and \( C \) (capacitance). The characteristic impedance for the PM is given by

\[
Z_{PM}^c = \sqrt{\frac{R + j\omega L}{G + j\omega C}}
\]

with \( \omega = 2\pi f \) being the angular frequency and \( j \) being the imaginary unit. Each conductor is surrounded by a circular dielectric insulation, and the wires are densely packed in a binder. Depending on the construction of the cable, the interspaces between the dielectrics are filled with air or jelly. Hence, the binder medium is inhomogeneous. Unfortunately, analytical expressions for the per-unit-length parameters \( R, L, G, \) and \( C \) cannot be found for inhomogeneous multiconductor transmission lines, and one must resort to numerical solutions [19], [20].

In this paper, we are interested in the evolution of \( Z_{PM}^c \) as a function of the separation distance \( D \) between the two TPs. The conductor losses \( R \) are independent of \( D \), as both the copper resistance and the skin effect are only functions of the conductor material and diameter, and the proximity effect can be safely ignored as soon as the separation distance is larger than twice the wire diameter [16], [20]. The dielectric conductance \( G \) depends on the dielectric thickness and will therefore decrease with increasing \( D \). However, for practical lines, this contribution will be negligible compared to \( j\omega C \).

As mentioned in [21] and [22], ignoring the dielectric insulation and considering the medium as homogeneous changes the capacitance values only slightly. This assumption is realistic for telephone binders as the interspaces are small, and the permittivity of the gel is close to the one of the insulation material. The capacitive coupling \( C \) has been approximated numerically as described in [19], and verified with a field simulator (Ansoft Maxwell). If only the two excited TPs are considered in a homogeneous medium (polyethylene), the capacitive coupling \( C \) was found to be inversely proportional to \( \sqrt{D} \). The inductive coupling \( L \) is related to the capacitive coupling \( C \) through the magnetic permeability \( \mu \) and the dielectric permittivity \( \varepsilon \) of the medium \( (LC = \mu\varepsilon) \), [22]; hence, \( L \) evolves proportionally to \( \sqrt{D} \). Due to the slight inhomogeneity of the dielectric insulation, the capacitive coupling and inductive coupling will still decrease and increase with the separation distance \( D \), respectively, although another law might be followed than \( \sqrt{D} \).

In summary, although an analytical expression for \( Z_{PM}^c \) as a function of the separation distance \( D \) between the two TPs cannot be found, the combined effect of the distance \( D \) on \( R, L, G, \) and \( C \) will cause \( Z_{PM}^c \) to increase with increasing distance. Hence, the theory predicts that two TPs in different binders will have a higher characteristic impedance than two TPs in the same binder. This has been verified by laboratory measurements. The characteristic impedance in PM \( (Z_{PM}^c) \) was calculated through an open and a short measurement [23]. The following two scenarios were considered.

a) “Same binder” scenario (Fig. 9): Two TPs share the same binder over the complete line length. The direct path is formed by the two wires of pair \( N_X \) in binder \( X \), and the return path is created by pair \( M_X \) in the same binder \( X \).

b) “Different binder” scenario (Fig. 8): Two TPs are located in different binders over the complete line length. The direct path is formed by the two wires of pair \( N_X \) in binder \( X \), and the return path is created by pair \( M_Y \) in another binder \( Y \).

Fig. 7 shows the results for three cable types: France Telecom (FT) cables with conductor diameters of 0.4 and 0.6 mm and a British Telecom (BT) cable with a conductor diameter of 0.5 mm. It confirms that the characteristic impedance in PM is indeed larger when the two TPs are situated in different binders. The difference is particularly pronounced at lower frequencies (<500 kHz). Therefore, it can be interesting to use only the low-frequency information for binder identification purposes. We also note that, similar to the characteristic impedance in pairwise differential mode, the characteristic impedance in PM is not monotonically decaying.

D. Binder Identification

As described earlier, two TPs in different binders (Fig. 8) will have a high characteristic impedance. This will create a strong mismatch with the (lower) impedance of the measurement device. By consequence, a strong near-end reflection will be visible in the time-domain response. Moreover, as most energy is already reflected at this point, only a small portion will travel along the line and contribute to the reflection from the line end. In contrast, when the two TPs are situated in the same binder (Fig. 9), the characteristic impedance is small.
Fig. 8. Two TPs located in different binders over the complete line length ("different binder" scenario).

Fig. 9. Two TPs sharing the same binder over the complete line length ("same binder" scenario).

Fig. 10. (Dashed line) For two TPs in the same binder, the end reflection is visible in the measured time-domain response; (full line) for two TPs in different binders, the end reflection does not stand out.

Hence, the mismatch at the measurement device will be small, and most energy will be inserted onto the line. As the signal travels along the line, standing waves will be created in the frequency domain. At the encounter with the open line end, a strong reflection will occur in the time-domain response. These completely different behaviors will allow us to identify whether the two TPs are situated in the same binder or not.

These expectations have been verified by laboratory measurements. The two setups in Fig. 8 ("different binder" scenario) and Fig. 9 ("same binder" scenario) have been constructed with FT lines of 1000 m. Fig. 10 shows the time-domain responses. As expected, when the TPs are situated in the same binder, the near-end reflection (at $t = 0 \mu s$) is smaller than that for TPs in different binders, and the reflection from the line end (at $t = 10 \mu s$) stands out more clearly with respect to the intermediate reflections.

Fig. 11 shows the measured one-port scattering parameter in the frequency domain. As expected, $|S_{11}^{PM}|$ is much higher when the two TPs are situated in different binders. Remember that the one-port scattering parameter is defined as the ratio of the reflected wave to the incident wave. Hence, a high magnitude means that a large part of the signal is reflected. Moreover, for TPs in different binders, no clear periodicity is present in the measurement. This is in contrast with the "same binder" scenario, which shows standing waves with a periodicity related to the line length.

The influence of the line length is detailed in Fig. 12 for the "same binder" scenario. The shorter the measured line, the lower the losses due to attenuation, and hence, the higher the magnitude of $S_{11}^{PM}$. The shorter the line, the larger the periodicity in $S_{11}^{PM}$, as these quantities are inversely proportional. As such, one can consider the "different binder" scenario as an extreme case of the "same binder" scenario, i.e., one with zero common length and infinite periodicity.

The aforementioned measurements (Figs. 10 and 11) show that it is possible to make a distinction between TPs in the same...
binder and TPs in different binders by analyzing the phantom measurements in the time or frequency domain. However, a telephone subscriber loop rarely consists of a single line connecting the central office to the customer. Therefore, it is possible that two TPs run along for a certain time and then split up. In that case, the phantom measurements also offer the possibility to determine the position where the TPs split. The following two supplementary scenarios are considered to cover these cases.

c) “Fully common” scenario (Fig. 13): Two TPs lie together in a first binder and together in a subsequent binder. The direct path is formed by the two wires of pair $N_X$ in binder $X$ in cascade with the two wires of pair $N_Y$ in binder $Y$. The return path is created by the two wires of pair $M_Y$ in binder $Y$ in cascade with the two wires of pair $M_X$ in binder $X$.

d) “Partly common” scenario (Fig. 14): Two TPs first share a common binder and then split up into different binders. The direct path is formed by the two wires of pair $N_X$ in binder $X$ in cascade with the two wires of pair $N_Y$ in binder $Y$. The return path is created by the two wires of pair $M_Z$ in a third binder $Z$ in cascade with the two wires of pair $M_X$ in the common binder $X$.

In the “fully common” scenario (Fig. 13), the characteristic impedance will be in the same order of magnitude in the first binder $X$ and in the subsequent binder $Y$. Hence, only a small reflection will occur at this junction. As in the “same binder” case (scenario a), a strong reflection will occur at the open line end. In contrast, for the “partly common” scenario (Fig. 14), the characteristic impedance will suddenly increase when transferring from the common binder $X$ (low impedance) to the different binders $Y$ and $Z$ (high impedance). Hence, a strong reflection will be created at the junction. Most of the energy will already be reflected here, and as in the “different binder” case (scenario b), a low reflection will occur at the end of the line.

These expectations have been verified by laboratory measurements, where all TPs had a line length of 1000 m. We also measured binder $X$ without any second line connected for comparison. The obtained time-domain responses are shown in Fig. 15. As expected, when the TPs split (thin gray line), a strong reflection is created at $t = 10 \mu s$ (the junction), while the end reflection (at $t = 20 \mu s$) is not visible. The reflection at the junction is almost as large as that when no second line segment was connected after binder $X$ (bulleted line). This means that the “partly common” scenario behaves as if no second binder $(Y/Z)$ is connected. In contrast, when the TPs continue in a second common binder (thick gray line), only a small reflection is created at the junction, and the end reflection is clearly visible despite the total distance of 2000 m.

Similar conclusions can be drawn from the one-port scattering parameter shown in Fig. 16. When the TPs split (thin lines), the one-port scattering parameter shows standing waves with a large periodicity, corresponding to the line length of binder $X$. Moreover, the measured curves are almost independent of the type of cable that is connected after binder $X$. The one-port scattering parameter behaves as if there was no second line segment (compare with the “open” case). In contrast, for the “fully common” scenario (thick lines), the one-port scattering parameter has a lower periodicity, corresponding to the increased total length of binder $X + Y$. Hence, if the TPs coexist in the same binder only over a certain distance, an analysis of the phantom measurements in the time or frequency domain can be used to determine the distance where the TPs split.

E. Discussion

The presented results open the way for binder identification, by analysis of phantom measurements in the time-domain response or the one-port scattering parameter. The exact implementation is not in the scope of this paper; however, some ideas of possible implementation are given in the following. The information from these phantom measurements can, of course, be combined with other information, e.g., a priori information or information from pairwise differential measurements.
Fig. 16. Measured $|S_{11}^{PM}|$ for (thick lines) the “fully common” scenario and (thin lines) the “partly common” scenario. The (bulleted line) measurement of a single line is added for comparison.

1) If a reflection is found in the time-domain response which corresponds to the one of an open end, then one can conclude that the two cables coexist up to this distance.

2) If the periodic behavior is absent in the frequency-domain representation of the one-port scattering parameter, then the two TPs are situated in different binders.

3) Pairwise differential measurement can be used to identify the lengths of the individual pairs. Next, one can check with phantom measurements if the end reflection is clearly visible. If yes, the TPs coexist over the complete length. If not, this means that most of the energy was lost earlier on the line. The presence of a strong reflection before the end reflection indicates the distance at which the TPs split.

The influence of the chosen pairs was also investigated. For this, one pair (acting as the forward path) was kept fixed, and the return pair was varied over the binder. If the TPs are situated in different binders, the choice of the return pair has almost no influence on the measurement (see Fig. 17). In contrast, when the TPs are situated in the same binder, the geometry of the binder comes into play (see Fig. 18). First, the capacitive coupling will slightly vary as a function of the relative position of the two considered TPs within the cable binder. Moreover, interposed TPs in the binder may act as an electric screen, as such lowering the capacitive coupling between the two TPs under consideration [24]. Nevertheless, the coupling between two nonadjacent TPs within one binder is expected to still be significantly higher than the coupling between two TPs in different binders for the following reasons: 1) The dielectric inside the binder (e.g., polyethylene) has a higher electric permittivity than air, which is the medium between different binders; hence, the electric fields will preferably stay within one binder; 2) binders are often shielded (e.g., with aluminum), as such further lowering the capacitive coupling between different binders.

Fig. 17. Measured $|S_{11}^{PM}|$ for different pairs in the “different binder” scenario: The used pair does not have much influence.

Fig. 18. Measured $|S_{11}^{PM}|$ for different pairs in the “same binder” scenario: The chosen pair has a strong influence.

When developing an algorithm for binder identification based on phantom measurements, one must first make a statistical study of the variance of $Z_{PM}$ within one binder for the considered cable type. This will allow gaining knowledge about which variations can be considered to be normal and hence defining a threshold whereupon to base the decision criterion about the location of the TPs.

IV. CONCLUSION AND FUTURE WORK

In this paper, we have shown that binder identification based on pairwise differential measurements is challenging because the measurements are sensitive to the nonuniformities along the TP. We have proposed a new measurement setup to measure differentially between two TPs (PM), which permitted us to identify whether two TPs were in the same binder or not. If they were only partly in the same binder, the distance at which they
split could be identified as well. The obtained results present a proof of concept, which open the way for binder identification applications with phantom measurements. The next steps are as follows: 1) to verify the results in the field (e.g., on binders with a higher number of TPs); 2) to develop an algorithm for automatic binder identification (taking the variance of the measurements into account); and 3) to adapt the modems for phantom measurements (simultaneous measurements of two TPs are needed).

REFERENCES


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