Channel Characterization for Underwater Broadband PLC Sensor Networks

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***Abstract*—For the tasks of navigation and obstacle detection, underwater and surface vehicles mostly rely on sonar, which uses a number of spatially distributed acoustic sensors. In this paper we explore the characteristics of linear bus structures, which is the natural choice for such an underwater sensor network, combining both power and data transmission capabilities, using only two wires. The measurement and modelling results of cables and a bus structure under changing pressure conditions are introduced. These results are essential for the development of a new broadband power line communication (PLC) system.**

I. Introduction

Virtually all underwater and many surface vessels are equipped with sonar, which is usually the only device capable of sensing the far-field environment under water. The transmission of digitalized acoustic data from outboard sensors, or hydrophones, to the inboard signal processing units is getting much more challenging, as the number of acoustic sensors, the distances between them, and their sampling rate and bit resolution increases. A typical future sonar system consists of hundreds of single hydrophones, producing a data flow of around 1 Gb/s.

The appropriate data transmission system is forced to be wire-line: because of the high attenuation of radio or optical waves under water, a wireless system would be very inefficient [1], especially on the typical sonar-array lengths of 100 to 500 meters. Besides, such a system would have to deal with a high diversity of channel conditions, because of extremely different water qualities (temperature, salinity, turbidity). Because of mechanical restrictions, the number of active components (like switching nodes) should be kept as low as possible, optimally not using such components outboard at all. It is in fact possible, keeping in mind that the power distribution network, being a linear bus topology, would already provide a communication path.

Nowadays, Power Line Communications (PLC) is a rather mature technology, commercially available for in-house AC power wiring (e.g. Homeplug AV, IEEE 1901, G.9960 [2]) and in the smart-grids field. Other examples of PLC include studies for on-board control networks on aircrafts [3], [4], ground vehicles [5], [6], ships [7], [8] or in embedded robotic systems [9], [10]. The research in this field mostly concentrates on providing a reliable low throughput (around 10 Mb/s) narrow-band link.

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This paper introduces the first steps in developing a new broadband PLC transmission system, Multi Carrier Twisted Pair Bus (MC-TPB), for underwater sensor networks. The suggested underlying topology is a linear bus, sometimes called multi-point architecture, similar to the topology found in coaxial cable networks or in-house low-voltage power distribution networks. Compared to the latter, an underwater linear bus is a much better controlled and transmission-friendly environment: due to static operation there are no switching currents and impedances are time-independent.

The power wiring typically limits the capacity of a broadband PLC system in two ways: the practically available bandwidth is reduced due to high attenuation and the power spectral density is artificially limited to reduce emissions. The MC-TPB system for underwater sensor networks can potentially avoid both limitations: being located outside the vehicle, the wiring has a natural outer shield - the water - practically zeroing the emissions. Besides, we propose using twisted pair cables of at least Category 5e for broadband differential mode data transmission (with the available bandwidth of 100 MHz) and common mode power distribution, without using extra power wiring.

Due to its location outside the vehicle, the cables are exposed to the quite aggressive underwater environment: high pressure, changing temperatures and moisture are the typical influencing factors. Even though, special underwater cables are developed to cope with such an environment, there are no publications, to the authors' knowledge, describing the exact influence of environmental factors, like pressure, on the electrical characteristics of underwater cables. This paper closes the gap, providing the corresponding measurements and modeling results under normal and high pressure.

The rest of the paper is organized as follows: Section II describes the measurement methods and setup. Section III provides information about the techniques used to model cables and the whole bus structure. The results of measurements under normal and high pressure and the corresponding modeling curves are provided in Section IV. Conclusions are given in Section V.

II. Measurement setup

All measurements were done using a network analyser (Rhode&Schwarz ZVR) with the following parameters:

- Source power: -10 dBm

- Intermediate (mixer) frequency: 1 kHz
- Measurement bandwidth: 250 kHz-125 MHz
- Number of frequency points: 2001
- Averaging factor: 10
- Unbalanced port impedance (Z_s): 50 Ω

Two types of measurements were carried out: single-port, to determine the transmission line parameters of different cable types; and two-port, to measure the transfer function of a linear bus structure. Both the cables and the bus were put into a water-filled pressure tank and were measured at five pressure levels: 1, 11, 31, 51, and 71 bar, roughly corresponding to the pressure at sea depths up to 700 meters.

The twisted pair cables and corresponding linear bus structures are balanced elements. A special HF transformer, the so-called balun (North Hills 0300bb model), is used in this setup to match impedances on both sides and for balanced/unbalanced conversion. A calibration with open, short, and termination differential standards was done before measurement to effectively remove the baluns from the results.

A. Single-port measurements

According to transmission line theory [11], a loop can be completely characterized by its complex propagation constant $\gamma = \alpha + j\beta$ and characteristic impedance Z_0. An open-short method, extensively used to determine the ADSL copper loop parameters (e.g [12]), is used in the following to find γ and Z_0 of three pieces of different underwater cables, produced by LEONI: 12 m UW100, 8 m UW130, and 8 m UW083.

The input impedance Z_{in} of a transmission line of the length l, loaded by termination impedance Z_L is given by

$$Z_{in} = Z_0 \frac{Z_L + Z_0 \tanh(\gamma l)}{Z_0 + Z_L \tanh(\gamma l)} \ , \tag{1}$$

where the secondary transmission line parameters are the unknown variables. Z_{in} is calculated according to

$$Z_{in} = Z_s \frac{1 + \Gamma_{in}}{1 - \Gamma_{in}} \ , \tag{2}$$

which is directly measured by the network analyzer at the input port of the balun. Two independent single-port measurements with different values for Z_L are needed to find the unknown secondary transmission line parameters. The system of equations has a simple solution, if the values $Z_L = 0$ (short circuit) and $Z_L = \infty$ (open circuit) are used. Using Eq. (1),

$$Z_{in}^S = Z_{in}|_{Z_L=0} = Z_0 \tanh(\gamma l) \ , \tag{3}$$

$$Z_{in}^O = Z_{in}|_{Z_L=\infty} = \frac{Z_0}{\tanh(\gamma l)} \ . \tag{4}$$

The secondary transmission line parameters can then be calculated as

$$\begin{aligned} Z_0 &= \sqrt{Z_{in}^S Z_{in}^O} \cdot \exp^{jn\pi} \ , \\ \gamma &= \operatorname{atanh}\left(\sqrt{\frac{Z_{in}^S}{Z_{in}^O}} \cdot \exp^{jn\pi}\right) + jm\pi \ , \\ n &\in [0,1], \quad m \in N_0 \ , \end{aligned} \tag{5}$$

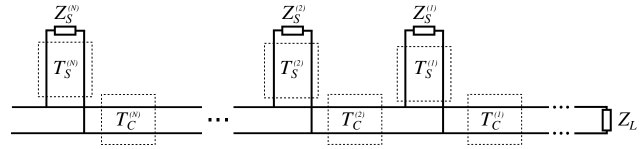


Fig. 1: Linear bus topology

where the terms with multiples of π represent the two solutions of square root and the periodicity of inverse hyperbolic tangent, accordingly.

B. Two-port measurements

The frequency-dependent scattering parameters of a two-port device under test (DUT) being a rather simple linear bus structure have been measured employing the two-port network analyzer setup. The structure is in fact a segment with only 3 stubs of an actual underwater cabling, having 32 stubs. This real-world example has 2.5 m UW083 cable between the stubs and 2 m from last stub to the cable end and from the first stub to the receiver. First and second branches are made of 0.7 m UW100 cable and the third one is 5 m long. All the measurements were performed between the receiver connector and the third (longest branch) source node, while other nodes were left open and the end of the line was not terminated. A well-known Short-Open-Line-Termination (SOLT) calibration method is used to exclude the influence of coaxial cables and baluns on the measurements.

III. CHANNEL MODELING

A linear bus topology, as depicted in Fig. 1, is an example of a multipath PLC channel, as it has taps and branches, providing multiple paths for signal propagation. A simple modeling approach, with parameters selected according to the physical properties of the underlying structure (e.g. segment number and length), is to split the system in Fig. 1 into two-port network sections, represented by their ABCD matrices, and then calculate the ABCD matrix T_{Sys} of the whole system (which is also a two-port network) and its transfer function, using the cascade property [13]. A cable of length l (or actually, a transmission line) can easily be represented as a two-port network, characterized by its ABCD matrix, using its secondary parameters γ and Z_0

$$T_C = \begin{bmatrix} \cosh \gamma l & Z_0 \sinh \gamma l \\ \frac{1}{Z_0} \sinh \gamma l & \cosh \gamma l \end{bmatrix} \ . \tag{6}$$

A branching connection can be modeled as a shunt impedance across the main line

$$T_S = \begin{bmatrix} 1 & 0 \\ 1/Z_{in} & 1 \end{bmatrix} \ , \tag{7}$$

with $Z_{in} = \frac{AZ_S + B}{CZ_S + D}$, calculated from two-port network ABCD parameters of the branch, terminated by impedance Z_S. The system ABCD matrix is then a simple multiplication of N segment matrices from equations (6) and (7), according to the cascade property [14]

$$T_{Sys} = T_C^{(1)} \cdot T_S^{(1)} \cdot T_C^{(2)} \cdot T_S^{(2)} \cdot \quad \cdots \quad \cdot T_C^{(N)} \cdot T_S^{(N)} \ .$$

The transfer function $H_{abcd}(f)$ of the bus system can then be calculated from the ABCD matrix T_{Sys}, assuming the known impedances of the transmitter Z_S and the receiver Z_L as

$$H_{abcd}(f) = \frac{Z_L}{AZ_L + B + CZ_S Z_L + DZ_S} \ . \tag{8}$$

Similar to the system transfer function below, the insertion loss (the ratio between voltage on the load without and with the bus structure) of the system can easily be calculated as

$$IL_{abcd}(f) = -20 \log \left(\frac{Z_L + Z_S}{Z_L} H_{abcd}(f) \right) \mathrm{dB} \ . \tag{9}$$

A. Cable Parameter Modeling

Existing cable models can be arranged in the three major groups: analytical models, which use the physical background and take into account material properties and geometry (Kelvin, VUB, RLGC(f) [15], [16]); rational functions, which try to fit some measured curves without any physical modeling; and semi-empirical models (BT, KPN, and MAR [17]), which are physical models, improved by less-physical heuristics [18]. The second and third groups can have problems in time-domain simulations, because of non-causal behavior [19]. The real and imaginary part of the impedances in these models are typically independent, whereas they should correspond to Hilbert transforms, the model to be causal. In case of the MAR model this was taken into account, so that it is in fact causal [20].

According to [18], the MAR model is a good choice, as it is efficient, easy to estimate, and causal. It has already been used to model an Austrian cable in [21]. The series impedance and shunt-admittance of the MAR model are given by

$$\begin{aligned} Z_s(f) &= j\omega L_\infty + R_0 \left(\frac{1}{4} + \frac{3}{4} \cdot \sqrt{1 + \frac{as(f)(s(f)+b)}{s(f)+c}} \right) , \\ Y_p(f) &= \omega C_f \cdot (j + \tan\delta) \\ &= j\omega C_{1\mathrm{MHz}} \cdot (jf \cdot 10^{-6})^{-\frac{2\delta}{\pi}} , \end{aligned} \tag{10}$$

where

$$\omega = 2\pi f, \quad s(f) = \frac{\mu_0 jf}{0.75^2 R_0}, \quad C_f = \frac{C_{1\mathrm{MHz}}}{(f \cdot 10^{-6})^{2\delta/\pi}} \ .$$

The model has seven parameters:

- L_∞ is the high frequency inductance per km [H/km],
- R_0 is the DC resistance per km [Ω/km],
- *a, b*, and c are skin effect coefficients,
- δ is the shunt capacity loss angle (constant),
- $C_{1\mathrm{MHz}}$ is the capacitance per km at 1 MHz [F/km].

A typical method for estimating the appropriate values of these parameters is fitting the model values to the measurement results at given frequency points. The MATLAB simplex minimization routine can be used for this (non-linear) task. The most popular example is probably the Ordinary Least Squares (OLS) method, where the objective function calculates the sum of squared errors. Throughout this work, the M-Estimation with Huber weight function is used, being more robust than OLS and due to its computational simplicity and fast convergence.

IV. Measurement and Modeling Results

To study the behavior of underwater cables under high pressure, a water-filled tank was used. The tank control equipment has a quite low pressure precision (±5 bar), especially at low pressure levels, and has no automatic control. The measurement results can thus be interpreted relatively, showing the trend, but a precise mathematical description of physical phenomena is difficult to achieve due to these inaccuracies.

A. Underwater Cables

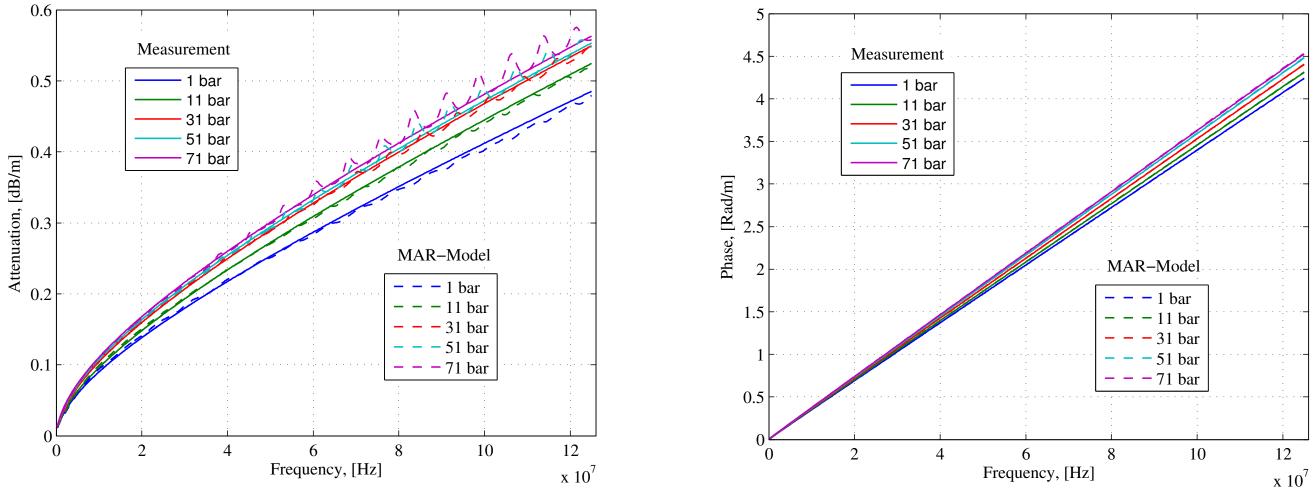
The behavior of the propagation constant under pressure can be studied for the UW100 cable, shown in Fig. 2. Both the attenuation in Fig. 2a and the phase in Fig. 2b show tendencies to increase with increasing pressure. This effect is quite pronounced with a roughly 16 % higher attenuation under 71 bar, compared to the normal pressure attenuation, measured at 100 MHz. The measured characteristic impedance in Fig. 3 shows some unexpected behavior starting at roughly 5 MHz, both in magnitude and phase, where rather flat curves were expected. Such behavior can be seen at high frequencies, measuring rather short cables (also found for instance in [22]) and can have several explanations. First, the difference of electrical length of short and open termination due to parasitic capacitances violates the assumption behind equations (5), used to calculate secondary line parameters. This causes errors, especially at frequency points, where the cable length corresponds to multiples of $\lambda/4$. The second reason could be the non-uniformity of the measured transmission line, which in all calculations above is assumed to be perfectly homogeneous. Nevertheless, the used model is physically-based and allows the prediction of the characteristic impedance at higher frequencies using only the lower frequency part of measured impedance and the complete curve of the propagation constant. In this case the modeled high-frequency values of magnitude and phase of the characteristic impedance show the physically expected behavior: flat magnitude curve, having its floor starting roughly from 50 MHz, and a zero phase floor. The parameters of a twisted pair cable, which is essentially a two-wire transmission line, can be defined as a function of its geometry (Chapter 10 in [11]) as

$$\begin{aligned} C &= \frac{\pi \epsilon_0 \epsilon_r}{\mathrm{acosh}(D/d)} , \qquad L = \frac{\mu_0 \mu_r}{\pi} \mathrm{acosh}(D/d) , \\ Z_0 &= \frac{1}{\pi} \sqrt{\frac{\mu_0 \mu_r}{\epsilon_0 \epsilon_r}} \mathrm{acosh}\left(\frac{D}{d}\right) , \end{aligned} \tag{11}$$

with primary transmission line parameters C and L, characteristic impedance Z_0, relative permittivity ϵ_r and permeability μ_r of the isolator between the wires with diameter d, separated by a distance D.

Assuming the constant permittivity and permeability, as well as almost constant wire diameter [1], the only parameter that can change strongly is the distance between the wires D. Rising pressure can possibly only reduce the distance between the conductors, decreasing the value of D. The expression for Z_0 in (11) depends on the inverse hyperbolic cosine, which

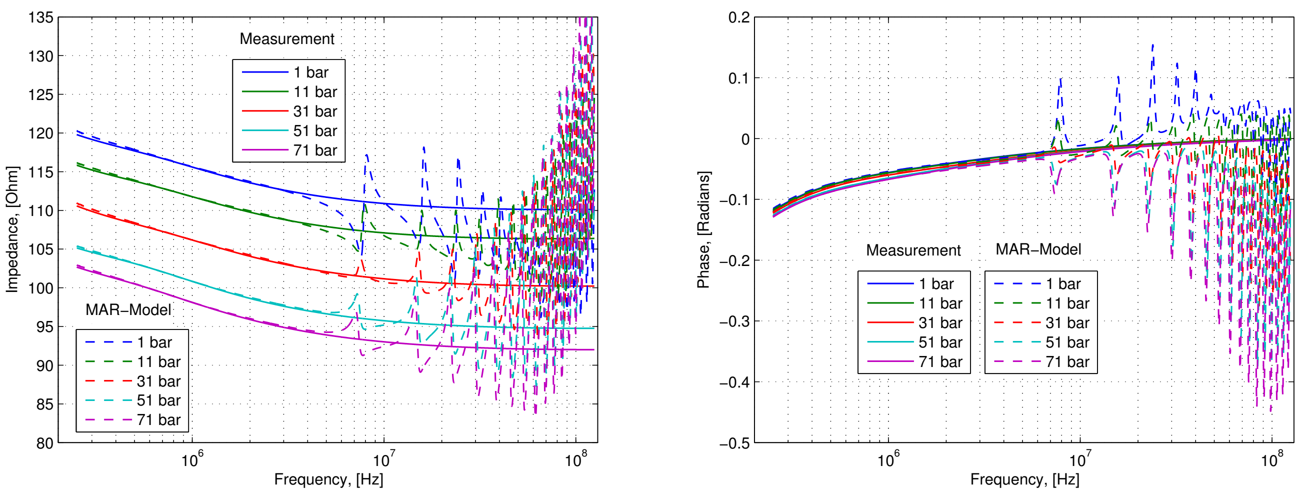
[1]Or at most getting reduced very slightly in case of stranded wires, which could be a reason for higher attenuation under pressure. Besides, the measurements under normal pressure afterwards have shown, that this change is not residual.



(a) Attenuation α

(b) Phase β

Fig. 2: Propagation constant γ of UW100 cable under pressure



(a) Magnitude

(b) Phase

Fig. 3: Characteristic impedance Z_0 of UW100 cable under pressure

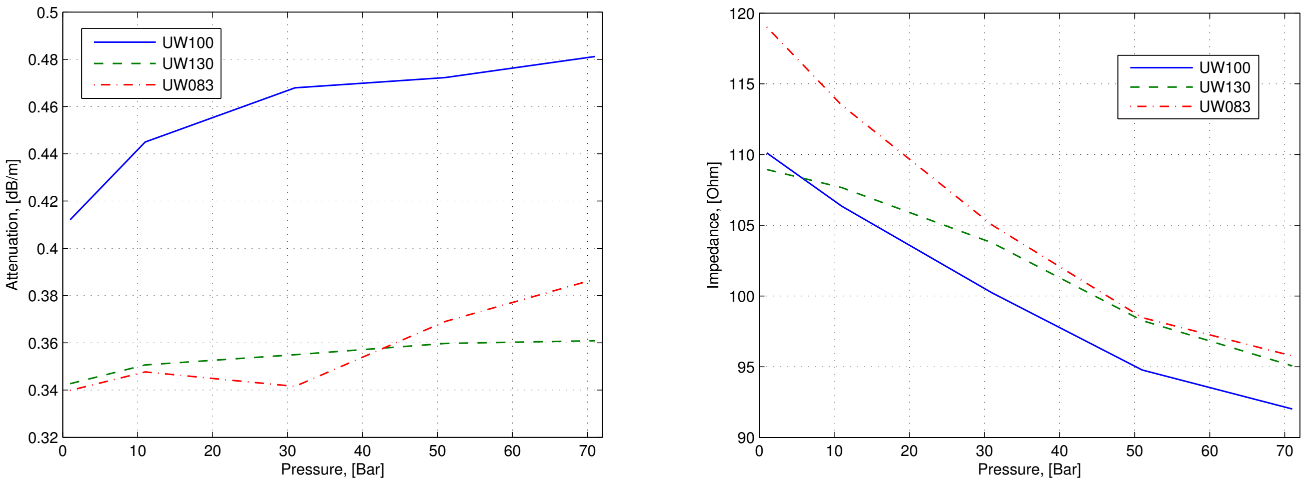
decreases with decreasing argument D. Thus, the theoretically predicted behavior would be a decreasing characteristic impedance with increasing pressure. As can be seen in Fig. 3a, this is actually the case with the measures underwater cables. Similar to the UW100 example, also the other underwater cables were measured. The results are depicted in a more compact form in Fig. 4, where propagation constant and magnitude of characteristic impedance at 100 MHz are shown.

All cables have shown increased attenuation and decreased characteristic impedance under pressure, UW100 and UW130 seem to reach the floor in characteristic impedance at 50 bar - depending on the materials and the mechanical structure, the cables are already compressed to some minimum and a further pressure increase does not effect their parameters in a reasonable range. Comparing UW130 and UW083, it is obvious that UW130 has better mechanical properties, resulting in a characteristic impedance less dependent on the pressure. Starting from 50 bar, both cables have almost the same Z_0, but the change of the impedance is about 20 % for UW083 and under 10 % for UW130, relative to starting values.

B. Bus Structure

For channel model verification purposes a bus structure with three taps (or nodes), has been measured. The measured S_{21} parameter can be directly interpreted as insertion loss (expressed in dB here)

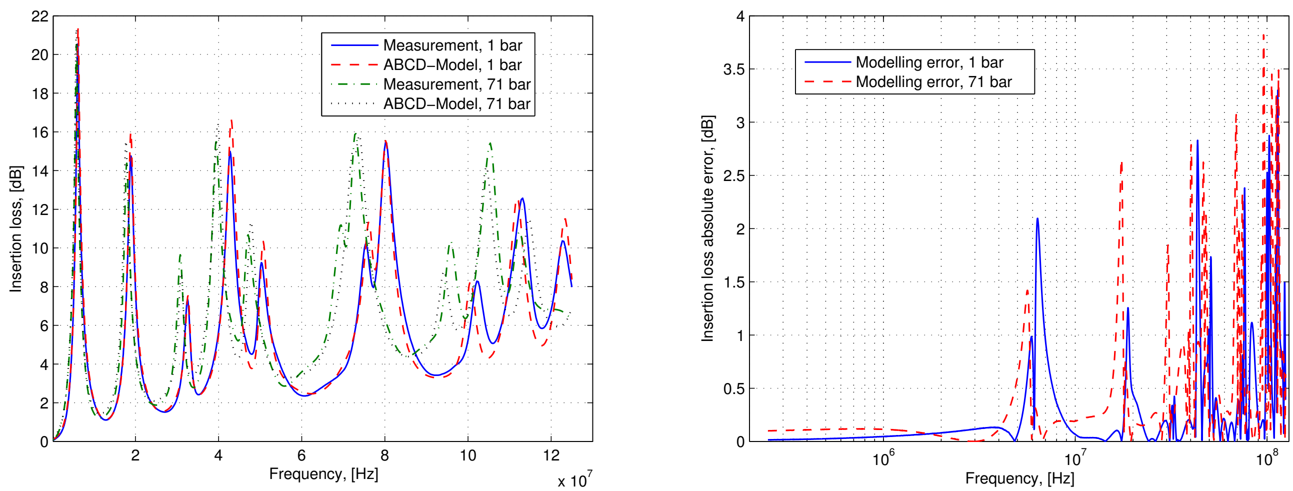
$$IL_{meas}(f) = -20\log_{10}(|S_{21}|)\text{ dB },$$



(a) Attenuation α

(b) Magnitude of Z_0

Fig. 4: Behaviour of different cables under pressure at 100 MHz



(a) Insertion loss

(b) Absolute error

Fig. 5: Insertion loss of a measured bus structure with 3 nodes

because both ports use the same, purely resistive reference impedance of 100 Ω.

The measured insertion loss is then compared to the modeled one, using Eq. (9) from Section III, shown in Fig. 5. The ABCD model is developed, using the previously measured and fitted cable models, with the corresponding segment lengths.

The PLC channel has an obvious frequency selectivity, as can be seen in Fig. 5a, with notches because of the bridge taps. Both under normal and high pressure levels this channel can be fairly well modeled, even though the maximum absolute error can be as high as 3 dB. These error peaks occur at the notches - regions of high attenuation - so that the relative error is still under 10 %. The connectors and slices, used to build up the bus system were not taken into account. This could be a reason for insertion loss modeling errors in Fig. 5b, especially at higher frequencies.

The absolute error is slightly higher under pressure. The reason for this could be the impedance mismatch between cables of different types, connectors and splices. The mismatch is getting higher with increasing pressure and neglecting connectors and splices in the model produces higher error levels under pressure.

V. Conclusion

The measurement and modeling results of underwater cables and a bus structure under changing pressure conditions were introduced, thus providing real-world characterization of the PLC channel for the future PLC transmission system. The MAR cable model was successfully used to simulate the electrical characteristics of the proprietary underwater cables. It was shown that high pressure results in increased attenuation and decreased characteristic impedance of up to 20 % at 100 MHz. The bus structure, based on underwater cables, was modeled applying two-port network theory rules to the ABCD-parameter segment representations. The high pressure does not only increase the overall attenuation, but also changes the channel selectivity, slightly moving the spectrum notches. It can be concluded that despite of the electrically rather well controlled environment, compared to indoor channels, the new PLC transmission system, MC-TPB, should nevertheless introduce an adaptation algorithm to cope with pressure changes.

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