WIDEBAND UTP CABLE MEASUREMENTS AND MODELLING FOR MIMO SYSTEMS

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ABSTRACT

This paper presents wideband MIMO cable measurements of a 10-pair 0.4mm UTP cable, which are then used to parameterise and verify the Joffe MIMO channel model for UTP transmission lines. The frequency dependance of the model parameters is pointed out, and prediction results based on various parameter sets are compared. The aim of the paper is to illustrate problems in the modelling accuracy which still exist at high frequencies.

1. INTRODUCTION

Crosstalk in Unshielded Twisted Pair (UTP) cables is the main impairment to the performance of Very-high-speed Digital Subscriber Lines (VDSL). The impact of crosstalk can be mitigated by Multiple Input Multiple Output (MIMO) systems, the performance assessment of which relies on models of the cable's transmission and crosstalk parameters. Two MIMO channel models have been proposed by Joffe [1] and Cioffi et al [2]. However, there are still open questions about the models' applicability and their appropriate parameterisation. There is a need for extensive wideband MIMO cable measurement data which would allow for verification of the channel models. This paper presents the results of measurements taken on test UTP cables, as well as results of fitting the data to Joffe's model [1].

2. CHANNEL MODELLING

The two favoured MIMO channel models [1] [2] have mathematically equivalent circuit models and corresponding ABCD matrices [2]. However, the underlying model parameters and the measurements necessary for their determination differ. The model of Cioffi et al [2] applies directly the multiconductor line theory from [3], using one of the wires as a reference "earth". While its theory is well developed, this model does not take advantage of the inherent symmetry of the wires in twisted pairs. Joffe's model [1] uses this symmetry and offers a physically more appealing set of parameters. Therefore, the latter has been chosen as the basis for the MIMO cable measurements presented in this paper.

A simplified version of Joffe's crosstalk and transmission model between two twisted pairs [1] is shown in Fig.1. The model parameters line capacitance C, resistance R, and inductance L are related to direct transmission, whereas the crosstalk capacitance C_{xa}, the equivalent capacitance imbalance d, and the difference in the mutual inductances between the wires M_m characterise the crosstalk. These parameters can be calculated as described in [1] from insertion loss and impedance measurements, which are discussed below.

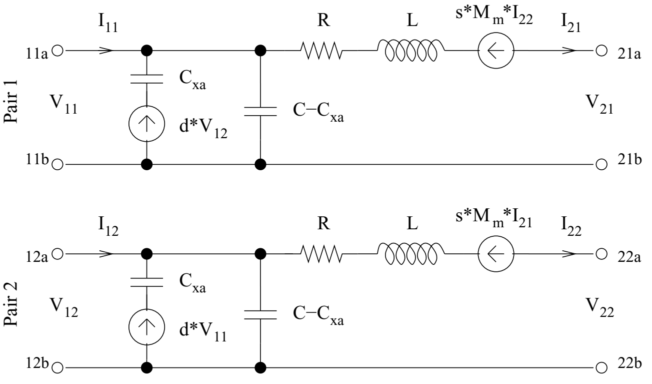

Figure 1: Joffe's simplified two-pair MIMO channel model for multi-pair UTP cables [1].

3. MEASUREMENT PLAN

The MIMO channel measurement plan proposed in [4] has been used as a guideline for the measurements presented here. Three cable lengths - 2m, 10m, and 150m of the same Poly-Ethylene Twin (PET) 10 pair 0.4mm UTP cable have been measured at 401 frequencies in the range from 0 to 30 MHz with 75kHz increments. However, the actual measurements have been geared towards Joffe's channel model [1], and include the types of insertion loss and impedances required for determining the parameters of this model.

The measurements have been taken with a network analyzer between any two pairs in the 10-pair cable, from both ends of the cables. The measurement plan is presented below, noting that terminal notations are as shown in Fig.1.

3.1 Insertion Loss Measurements

- Insertion loss between 100 Ω source at terminals 11 and 100 Ω load at terminals 21 (transfer function).
- Insertion loss between 100 Ω source at terminals 11 and 100 Ω load at terminals 12, terminate ends 21 and 22 in 100 Ω loads (NEXT), or leave open circuit, or short circuit.
- Insertion loss between 100 Ω source at terminals 11 and 100 Ω load at terminals 22, terminate ends 12 and 21 in 100 Ω loads (FEXT), or leave open circuit, or short circuit.

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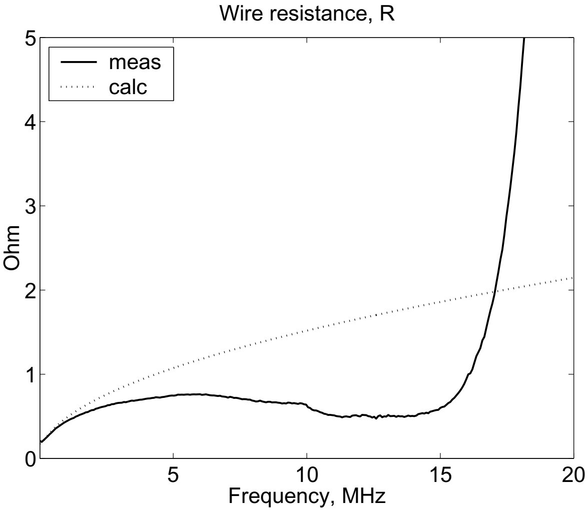

Figure 2: Measured and calculated [2] wire resistance *R* per metre of 0.4mm UTP in multipair cable.

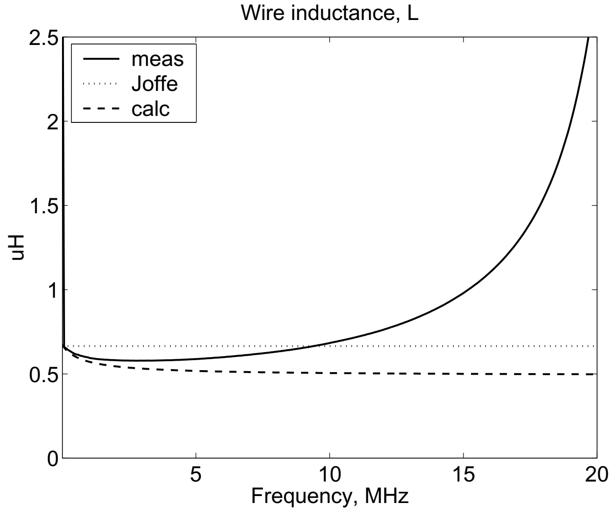

Figure 3: Measured, measured by Joffe at 10 KHz [1], and calculated [2] wire inductance *L* per metre of 0.4mm UTP in multipair cable.

3.2 Impedance Measurements

- Impedance between terminals 11a and 11b, with terminals 21 terminated in 100 Ω load, or left open circuit, or short circuit (input impedance).
- Impedance between terminals 11 and 12, where 11a and 11b are short circuited, 12a and 12b are short circuited. Terminals 21 and 22 are either left open circuit, or all 21a/21b/22a/22b are short circuited, or with a 100 Ω load between 21a/21b and 22a/22b (impedance between lines).
- Impedance between terminals 11a and 21a, and between 11b and 21b (impedance of a wire).

4. RESULTS

The measurement results for the 2m cable piece have been used to obtain the relevant model parameters. The channel model has then been used to calculate the transfer function and crosstalk for a 10m line, and the predictions have been compared with measurements of the 10m cable piece.

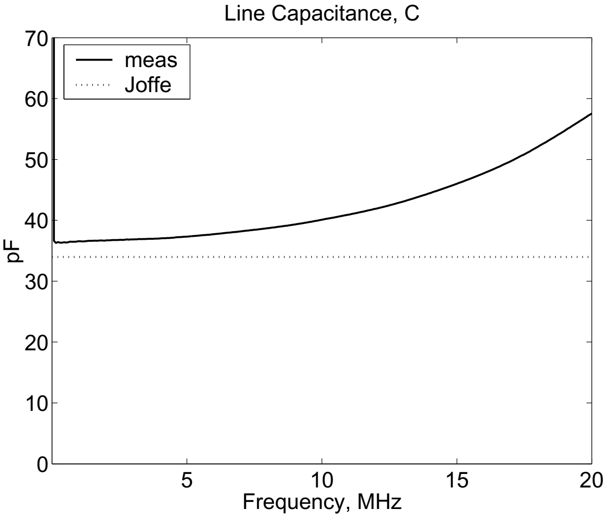

Figure 4: Measured and measured by Joffe at 10 KHz [1] line capacitance *C* per metre of 0.4mm UTP in multipair cable.

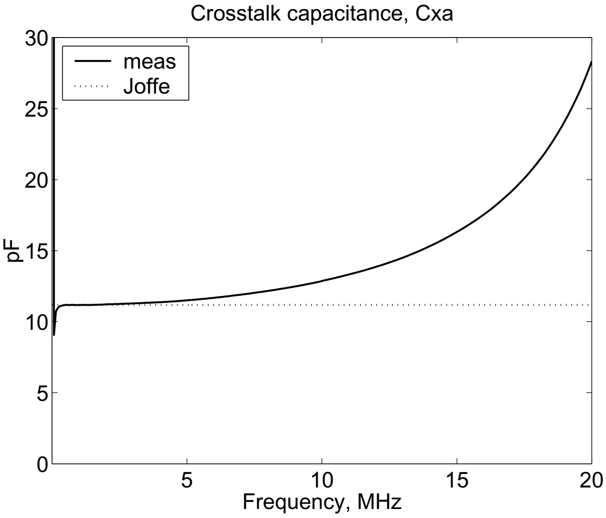

Figure 5: Measured and measured by Joffe at 10 KHz [1] crosstalk capacitance C_{xa} per metre between two 0.4mm UTPs in multipair cable.

4.1 Model parameters

The measured line resistance *R* (Fig. 2) shows a perfect match with theoretical calculations [2] up to 1 MHz. As the frequency increases, the theoretical and measurement results diverge, most likely because of a resonance observed in the 2m cable measurements at 22 MHz. Similarly, the measured wire inductance *L* (Fig. 3) is close to the theoretical values [2] at low frequencies, but diverges at the higher frequencies. The measured line capacitance *C* (Fig. 4) and the crosstalk capacitance C_{xa} (Fig. 5) also increase at high frequencies although theoretically they should be virtually frequency independent. The capacitance imbalance *d* and the

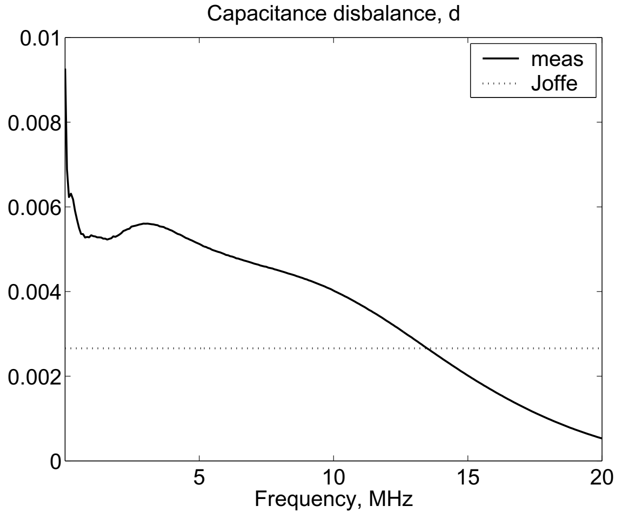

Figure 6: Measured and measured by Joffe at 1 MHz [1] capacitance imbalance *d* between two 0.4mm UTPs in multipair cable.

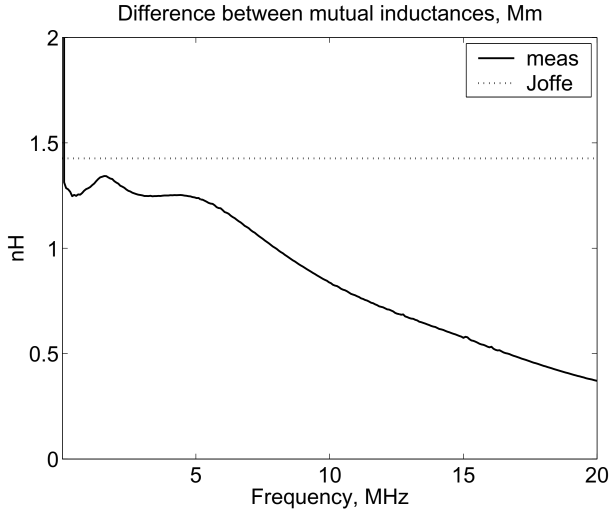

Figure 7: Measured and measured by Joffe at 1 MHz [1] difference in the mutual inductances M_m per metre between two 0.4mm UTPs in multipair cable.

difference in the mutual inductance M_m have a complex frequency dependence, but exhibit a general trend to decrease at higher frequencies (Fig. 6 and 7).

It is interesting to note that the current results for L, C, and C_{xa} at low frequencies agree well with Joffe's measurement at 10 kHz [1]. Note also that d obtained in the current measurements is generally higher, and M_m - lower than those reported by Joffe in [1].[1] Differences in d and M_m measured on different cable samples can be expected since they are related to the defects in the cable symmetry and therefore depend on the cable structure and the deformations in the particular cable piece. It should also be noted that at higher frequencies the obtained parameter values are affected by the fact that the signal wavelength becomes comparable to the length of the measured cable piece, which leads to distortions in the measurement results [1].

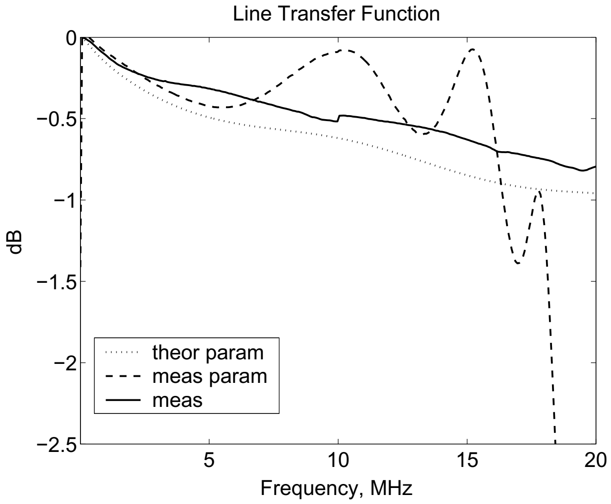

Figure 8: Line transfer function measured directly (meas), or calculated using theoretical parameters [1,2], or measured parameters for a pair from a 10m, 10-pair UTP cable.

4.2 Model predictions

The calculations have been carried out for a line length of 10 m, assuming the line is made up of cascaded elementary units of 1 cm each. Three sets of model parameters have been used - the measured frequency-dependent parameters presented above, the parameter values utilised by Joffe [1] (which for the normal transfer parameters R, L, and C virtually co-incide with the theoretical ones [2]), and a mixture of theoretical values for the normal transfer parameters, and measured values for the crosstalk. The predictions have been compared to measurements of a 10m cable piece of the same drum as the 2m piece used to determine the parameters.

The calculated line transfer function (Fig. 8) is close to the measured one at low frequencies, but diverges as the frequency increases. The measured parameters in particular lead to predictions with large ripples in the high frequency spectrum, whereas the theoretical parameter values [2] provide a relatively good match across the whole frequency range.

For far-end crosstalk (FEXT), Joffe's parameter set yields a prediction which is higher than the measured FEXT, is unnaturally smooth and does not model the ripples evident in actual measurements (Fig. 9). The frequency-dependent parameter values lead to a much better fit for FEXT, which follows the ripples in the measured curve even at higher frequencies. The mixture of theoretical transfer and measured crosstalk parameters produces an estimate which follows the measured FEXT, but again is unable to predict ripples.

All parameter sets yield poor estimates for NEXT at higher frequencies (Fig. 10). The entirely measured parameter set reflects better the ripples in the near-end crosstalk (NEXT) measurements than the other two sets, but is still far from the actual measurements.

The results show that the model in [1] performs well at

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[1] The parameter values reported by Joffe in [1] have been measured at single frequencies - 10 kHz for L, C, and C_{xa}, and 1 MHz for d and M_m. However for the purpose of comparison they have been represented in the graphs with a straight line across the whole frequency range.

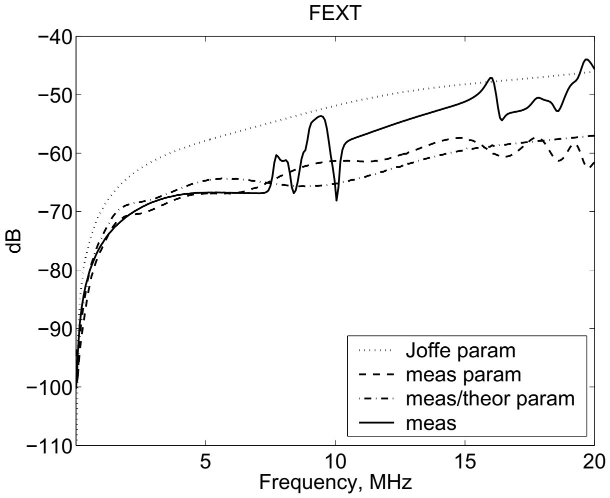

Figure 9: FEXT measured directly (meas), or calculated using Joffe's parameters [1], or measured parameters, or measured crosstalk parameters / theoretical normal transfer parameters [2], between two pairs in a 10m, 10-pair UTP cable.

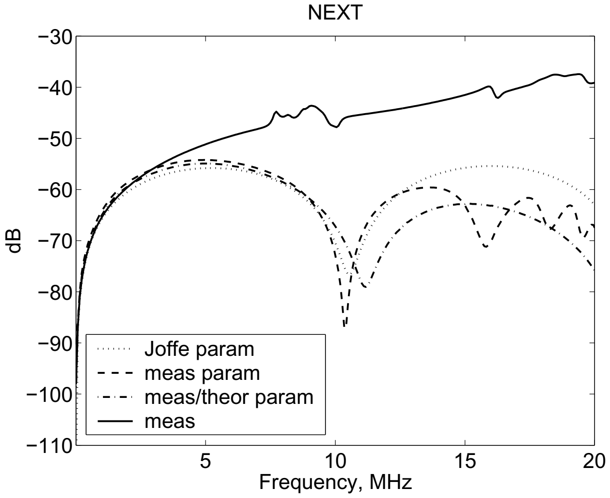

Figure 10: NEXT measured directly (meas), or calculated using Joffe's parameters [1], or measured parameters, or measured crosstalk parameters / theoretical normal transfer parameters [2], between two pairs in a 10m, 10-pair UTP cable.

frequencies up to 2 MHz, but yields poor results at higher frequencies. Using frequency-dependent parameters appears to give more accurate crosstalk predictions, however the transfer loss estimate is poor. If measured crosstalk parameters and theoretical transfer parameters are utilised, the transfer function estimate is better, but the crosstalk estimates - worse than the entirely measured parameter set.

5. CONCLUSIONS

This paper has presented wideband MIMO cable measurements of a 10-pair 0.4mm UTP telephone cable. The measurement results have been used to determine the parameters of Joffe's channel model [1]. The calculated parameters have been compared to the values reported in [1] and the frequency dependance of the crosstalk parameters has been pointed out. The channel model predictions based on various parameter sets have been compared, and it was shown that the model in [1] with homogenious parameter values performs well only up to about 2 MHz. There may be a scope for improved estimates at higher frequencies if frequency-dependent parameters are used, which however can cause deterioration of the pair loss predictions. A trade-off can be achieved by setting only the crosstalk parameters to be frequency dependent, which achieves good pair loss estimates and a better fit for the crosstalk predictions than if constant crosstalk parameters are used. Nevertheless, there are still problems in the modelling accuracy at high frequencies.

This research was stimulated by the need for accurate channel modelling for MIMO systems, which have the potential to mitigate the impact of crosstalk, thus increasing the usable bandwidth and consequently the achievable bit rate of VDSL systems.

Acknowledgements

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