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EXPERT SYSTEM FOR THE IDENTIFICATION AND CLASSIFICATION OF THE LOCAL LOOP

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Abstract – The Expert System, which is described in this paper, constitutes a fundamental unit of a general measurement system, which is capable to perform an xDSL (arbitrary Digital Subscriber Line) loop qualification by means of time-domain reflectometry (TDR).

The goal of the measurement system is to estimate the theoretical channel capacity of the local loop, which connects the customer premises (CP) to the central office (CO), based on TDR (time-domain reflectometry) measurements and noise PSD (Power Spectral Density) measurements at the CO. These measurements are processed using advanced digital signal processing (DSP), artificial intelligence (AI), and system identification to estimate the loop transfer function and noise PSD at the CP, which are needed for the estimation of the capacity.

Keywords intelligent measurement systems, expert systems, local loop.

1. INTRODUCTION OF SELT

In the last years, DSL has become a mature market delivering services such as high speed internet access to a large portion of the residential population. High speed Internet access has been the first application to deploy ADSL (Asymmetric DSL) with success. However, new applications such as video over DSL require still higher bitrates, higher QoS, improved stability etc. Therefore, continuous investment in xDSL is needed to guarantee future applications.

Many standardised xDSL (ISDN, ADSL, SHDSL, VDSL) systems are currently widely deployed worldwide, of which ADSL still is the leader and becomes more and more a commodity. But, new xDSL variants such as ADSL2, ADSLplus, long reach ADSL and VDSL are appearing as reaction to new service applications or telecom operator requests.

To date, DSL deployment has been driven primarily by the need to provide basic High-speed Internet (HSI) service to the largest population possible, by means of standardised ADSL technology. Operators have succeeded in doing this by focusing the deployment of DSL infrastructure in the COs where mass coverage could be achieved at the lowest cost. As DSL deployment in COs continues, there are new demands driven by increased penetration rate, demand for service in unserved areas and a growing appetite for enriched content. These dynamics give rise to two fundamental challenges for operators today:

1. Extending coverage to yet unserved areas;
2. Increasing bandwidth.

In many European countries, standard ADSL penetration from the Central Office is limited to ca. 90 % of the population. This is due to the limitations of current standard ADSL. In order to provide higher bandwidth tiers of service, it will be necessary for DSL providers to deploy remote equipment in areas which are designated as "Grey Zones" (these zones have sufficient bandwidth for basic High Speed Internet offerings, but have insufficient bandwidth from the CO for higher bandwidth services) as well as in the "Red Zones". This is depicted in Figure 1.

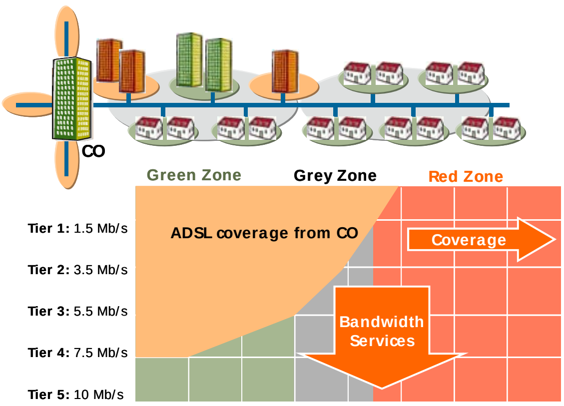

Fig. 1. Increasing the bandwith and coverage of ADSL towards **Grey** (moderate HIS) and **Red** (no serving) Zones.

Operators today are performing loop qualification to provide, support and troubleshoot xDSL service [1]. Up till recent, line testing has been performed using measurement equipment placed at the Central Office (CO) and at the Customer Premises (CP) side. This requires an expensive truck roll at the CP location, but the measurement is quite accurate. Recently, Single-

Ended Line Testing (SELT) has become a new and interesting topic [2], [3], [4], [5], [6], [7], [8]. The aim is to perform measurements at the Central Office only in order to obtain a reasonable estimate of the line quality. Therefore, the objectives of SELT are the prediction of the end-to-end transfer function of the loop, the gathering of knowledge of the loop topology (topography, line types and line lengths) and the identification of the disturbers at the receiver.

Once the channel topology and disturbers are known, the capacity in bits/s (e.g. for ADSL or VDSL) can be predicted. SELT measurements can be performed by stand-alone equipment or by the broadband modem itself doing the tests.

2. DESCRIPTION OF SELT

2.1 Measurement Quantities at CO

In order to determine the channel capacity of the local loop, in Measurement Science terms referred as the Device Under Test (DUT), two loop properties have to be identified:

1. the end-to-end Power Transfer Function (PTF) in a predefined termination impedance, e.g. 100Ω for ADSL;
2. the Power Spectral Density (PSD) at the receiver.

An estimation of the PTF should be obtained from a quantity independent from a test-head. This quantity must contain fundamental information about the loop but may not depend on the nature of the excitation signal and since plain Time Domain Reflectometry (TDR) is used the trace also depends on the shape of the injected pulse. Possible information carrying quantities are: the one-port scattering parameter $S_{11}(\omega)$ or the input impedance $Z_{in}(\omega)$ of the loop, which are mostly represented in the frequency domain.

The one-port scattering parameter $S_{11}(\omega)$ has been chosen to express the description of the loop's behavior and is defined as (see also Figure 2):

$$S_{11}(\omega) = \left.\frac{b(\omega)}{a(\omega)}\right|_{Z_{base}} \tag{1}$$

with $a(\omega)$ the incident voltage wave and $b(\omega)$ the reflected voltage wave both given in the base impedance Z_{base}.

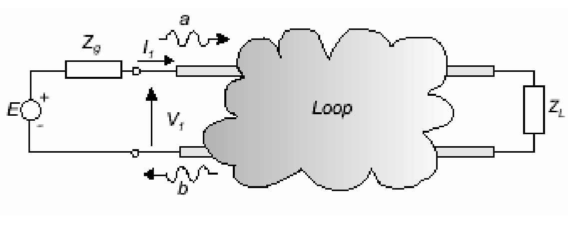

Fig. 2. The input port of a subscriber line and the corresponding electrical quantities.

To stimulate the DUT, multi-tone signals are chosen as excitation signals. $S_{11}(\omega)$ measurements are conducted after calibrating the analog front-end. Three $S_{11}(\omega)$ measurements are necessary to calculate a calibration data set and a very common choice is to use an open-ended, short-circuited and a loaded measurement port. Using these three measurements, a set of three frequency dependent coefficients can be calculated that allow the calibration correction of the raw $S_{11}(\omega)$ measurement.

2.2 Pre-Processing

The pre-processing will transform the obtained scattering parameter $S_{11}(\omega)$ into its time domain counterpart $s_{11}(t)$ also labeled the impulse response of the DUT [9]. The pre-processor deliverables are (see Figure 3):

1. The computation of a calibrated version of the impulse response; i.e. as if the impulse response would be obtained by an ideal measurement instrument matched to the line and placed at the calibration plane.
2. An estimate of the arrival time of the first significant reflection.

The impulse response $s_{11}(t)$ is further used by the topology classification algorithms.

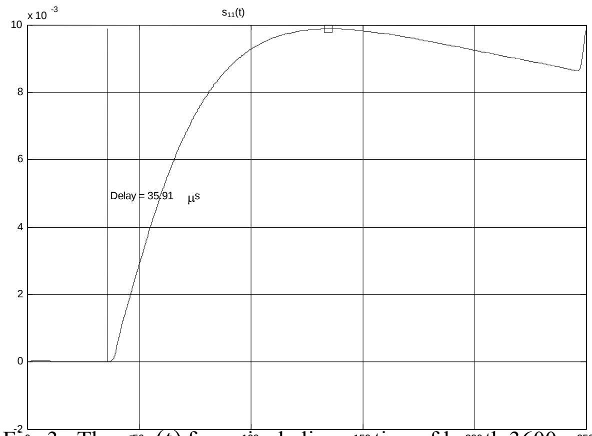

Fig. 3. The $s_{11}(t)$ for a single line section of length 3600m.

2.3 Topology classification

As soon as the preprocessor delivers a de-aliased version of the impulse response $s_{11}(t)$ a topology classification of the loop can take place. The goal of the classification is the provisioning of the frequency domain physical model of $S_{11}(\omega)$ and the corresponding starting values to be used in the loop identification procedure. The classification takes place in three phases and will be briefly outlined (a detailed discussion is found in [4]).

1. Firstly, the features of $s_{11}(t)$ are detected. Important features are the start, maximum and end position of an observed reflection. In practice reflections do overlap each other, which do complicate the feature detection of each individual reflection.

Some methods to separate reflections from each other do exist, but none of them is suited for a separate loop identification, because most existing methods [5], [10] use an embedded feature extraction, topology classification and identification method in contrast to the proposed sequential approach in this work. The iterative peak detection algorithm can be split up in three subparts:

a. The extrema and inflection points of $s_{11}(t)$ are detected;
b. A numerical prediction of the tail of the first peak is made using a mathematical function;
c. The overlapping part of the peak under study is replaced by the in section b estimated continuation of that peak.

A residual response can be calculated where after steps a, b and c can be repeated with this residual response. The iteration stops when the energy of the residue signal is below a predefined level.

2. Secondly, when the features of $s_{11}(t)$ are derived, a preliminary topology prediction is given using a probabilistic reasoning system. The supported topologies are

(L, LL, LLL, LTL,LTTL, LTLTL)

with *L* an inline segment and *T* a tap. This system, which derives knowledge from a data record is designed according to a belief network, and hence, uses Baye's rule as the basic reasoning principle. So, the most likely topology *T* given the fact that one knows the features of the peaks *F* is obtained as follows:

$$P(T \mid F) = \frac{P(F \mid T) \cdot P(T)}{P(F)} \tag{2}$$

The knowledge base $P(F \mid T)$ is inferred, by solving an optimization problem, from a user selected set of rules, e.g.

P(1st first peak | 2nd line segment not present) = 0.9

Unconditional rules or facts also exists, e.g. if an operator does not have bridged taps in its access network then *P(loops with taps)=0*. Two belief networks were designed. The first reasons on the signs of the peaks and the seconds one uses the positions of the peaks. A weighted average on the outcome of both networks produces the final topology estimation.

3. Thirdly, a Rule Based System (RBS) tries to interpret the previous topology prediction. It provides the most logic topology with the corresponding values for the delays and line types of each line segment of the loop. In order to guarantee a valid result, a priori information about the cable network is used as much as possible. Important a priori information are the existence of taps in a network, the wire gauge order in cascaded networks, the line types used in the network etc. The RBS system is deterministic, because it is build on an elaborated set of deterministic rules. In the beginning, the RBS reasons on features and gradually it adds more physical reality until a $s_{11}(t)$ curve is simulated for comparison with the real measured one. If an error is found then the solution will be improved or it will create of a new solution.

2.4 Loop identification

The last important phase consists in the identification of the calibrated measurement $S_{11}(\omega)$ with a parametric model $S_{11,m}(\omega, \boldsymbol{P})$, which is based on transmission line theory and twisted pair modeling. It is possible to construct such a model because the topology together with a set of initial values of the parameters $\boldsymbol{P}$, which have been previously determined, are available. A $S_{11}(\omega)$ Maximum Likelihood Estimator (MLE) was constructed for the parameter identification (an in-dept description is found in [2]).

The $S_{11}(\omega)$ estimator uses the VUB cable model [2], [11]. This model is based on the geometric and the material properties of a 2-wire line. The model covers the skin effect and the proximity effect in the behavior of the series-impedance of the (copper) conductors. The dielectric modelling is kept very simple because most lines use polyethylene as an insulation material.

The MLE has been constructed using an output error model and this involves that the following cost function C needs to be minimized:

$$C = \sum_{k=1}^{N} \frac{\left| S_{11}(\omega_k) - S_{11,m}(\omega_k, \boldsymbol{P}) \right|^2}{\sigma^2(\omega_k)} \tag{3}$$

with $\sigma^2(\omega_k)$ the variance of the measured $S_{11}(\omega)$ at the angular frequency ω_k. For long loops (length > 2km), impedance irregularities coming from the local non-homogeneities and connectors disturb $S_{11}(\omega)$ in the complete frequency band. These disturbing effects are removed by using a time window on $s_{11}(t)$ and hence $S_{11}(\omega)$ needs to be convolved with the Fourier transform $W(\omega)$ of that window. The cost function then becomes:

$$C = \sum_{k=1}^{N} \frac{\left| S_{11}(\omega_k) \otimes W(\omega) - S_{11,m}(\omega_k, \boldsymbol{P}) \otimes W(\omega) \right|^2}{\sigma^2(\omega_k) \otimes \left| W(\omega) \right|^2} \tag{4}$$

A Levenberg-Marquardt cost function minimiser is used. It combines the Gauss-Newton and gradient-descent procedures in an intelligent way [12].

2.5 Channel capacity estimation and prediction

Knowing the loop topology is of great importance for an operator to test, pre-qualify, debug and maintain a loop [8]. If the PSD of the noise at the receiver side is known, using a direct measurement or an estimation of the PSD, then in addition a bit rate prediction is possible. In order to obtain the theoretical channel capacity, Shannon's capacity formula can be used.

$$b = \sum B_i \log_2(1 + SNR_i) \quad \text{[bits/s]} \tag{5}$$

With B_i the bandwidth of sub-channel ‘i’ ($B_i = 4{,}3125 kHz$ for ADSL and VDSL) and SNR_i is the corresponding Signal-to-Noise Ratio at the receiver in that sub-channel.

3. MEASUREMENT RESULTS

The techniques explored in this paper have been developed and validated first on practical cables in well controlled laboratory conditions. At the VUB in Brussels, a cable network using cables from the Belgian operator Belgacom has been set-up, while at the premises of Alcatel in Antwerp, Alcatel's cables deployed by France Telecom have been used. Next, two measurement trials using real-life networks of operators have been set-up. The first one has been using the Belgacom network at the test site of Braine L'Alleud (CO) and Ophain (local distribution center) in Belgium. The next one has been organised at a cable farm in Lannion in France.

In Figure 4 the estimated $s_{11}(t)$ for 4 different pair numbers on a section of the Belgacom test network is plotted. The configuration is L-L-L-L-L and the according line lengths and types have been adequately resolved by the expert system. The expected bit rate is within a 5% error margin, and hence useful for practical prediction of the expectations regarding the connections for a particular customer.

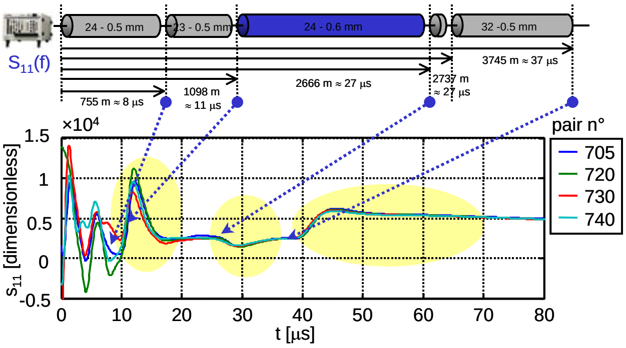

Fig. 4: The identified $s_{11}(t)$ of a Belgacom DSL network of total length = 3745m.

4. CONCLUSION

The LoopExplorer Expert System is a complete integrated system that demonstrates the capabilities of Single Ended Line Testing. This work was supported by the Flemish Community IWT. The system is currently a demonstrator and requires further testing in the field. Good topology predictions have been obtained for cascaded networks with acceptable estimates for the attainable bit rates.

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