Length Restrictions in Cable Testing

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Abstract

The big data era is asking for twisted pair cables capable of transmitting ever increasing data rates. While Cat5 Ethernet cables were defined for bandwidth of 100MHz , supporting data rates up to 1Gb/s over 100m channel length, Cat8 is designed for 2GHz, 40Gb/s, over 30m channel length. Although these requirements are well spelled out in the standards, the burden is shifted to the cable manufacturers that must properly characterize their products for certification purposes. Nonetheless, during the manufacturing process, cables of various lengths are produced and sent for qualification. With none standardised length, it is thus critical to apprehend your test system limitations in order to properly interpret your measurement results. This paper describes the impact of cable length on low frequency and high frequency parameters. It derives ATE (Automatic Test Equipment) system limitations and in the case of very long cable beyond system capability, highlights an extrapolation procedure.

Keywords: Twisted pair category cables, resistance, capacitance, attenuation, insertion loss, FEXT, ACR-F.

1. Introduction

Even if most of LAN cable standards, besides Cat8, use 100m as a reference length, questions arise on how to interpret results when using other cable lengths: either shorter, i.e. 50m or 30m for example for LAN cables, or longer like 305m or 500m or even few kilometres for telephone cables. The reasons to use different length could be economical to avoid too much wasting and/or an ease of processing and handling (measurement of complete drum or box quantity).

Testing is the only means to get the real performance of a cable. As such, it is of prime importance to define the measurement limitations in order to derive the low and high frequency parameters for various cable lengths. As explained in this paper, not measuring properly could lead to misinterpretations that can easily be explained by the physical boundary conditions of testing.

Nevertheless, in the case of long cable length for which measurement is not feasible beyond a certain frequency due to system limitation, a workaround is doable based on the extrapolation of the Insertion Loss (IL).

This paper is divided into three parts: the first one covers the low frequency parameters like Resistance or Capacitance; the second one is dedicated to the high frequency parameters like Attenuation/Insertion Loss, ACR-F etc... The last part describes the extrapolation procedure AESA has developed, along with and its intrinsic limitations.

2. Restrictions for Low Frequency Parameters

2.1 Theoretical Background

When measuring long cable length with the Wheatstone bridge method, the risk is to lose the synchronization between the voltage and the current due to dephasing from non-resistive components. This will make the values looking smaller and incorrect. Hence, we have to revert to the theory to calculate the maximum cable length within a certain acceptable measurement error.

Following transmission line theory [1] - [3] the input admittance of a cable is defined as:

$$Y_{in} = Y_c * \tanh(\gamma * l) \tag{1}$$

with l, the cable length and:

$Y_c = \mathrm{sqrt}(Y_0/Z_0)$	Characteristic admittance
$\gamma = \mathrm{sqrt}(Z_0 * Y_0)$	Propagation constant
$Z_0 = R_0 + j\omega L_0$	Impedance per unit length
$Y_0 = G_0 + j\omega C_0$	Admittance per unit length
$\omega = 2\pi f$	Angular frequency

R_0, L_0, G_0, and C_0 are the nominal loop resistance, inductance, conductance and mutual capacitance, respectively.

Developing the hyperbolic tangent in Taylor series and considering that $\omega L_0 << R_0$ and $G_0 \sim 0$ (lossless transmission line), (1) can be re-written as follows:

$$Y_{in} = Y_c\,(\gamma * l)\,[1 - 1/3(\gamma * l)^2 + 2/15(\gamma * l)^4 - 17/317(\gamma * l)^6 + \ldots] \tag{2}$$

or:

$$Y_{in} = j\omega C_0 l * (1 - 1/3 j\omega R_0 C_0 l^2 - 2/15(\omega R_0 C_0)^2 l^4 + \ldots) \tag{3}$$

Neglecting higher order terms and measuring only the imaginary part of the admittance, (3) simplifies to:

$$\mathrm{Im}(Y_{in}) \approx \omega C_0 l * (1 - 2/15(\omega R_0 C_0)^2 l^4) = \omega C_0 l * (1 + \varepsilon) \tag{4}$$

where ε represents the relative measurement error of $\omega C_0 l$.

2.2 Practical Limitations

In practical cases, we would like to measure the admittance of a cable within a certain accuracy or so-called acceptable relative measurement error, ε. However, per equation (5), the ε value will dictate the maximum possible cable length to be measured:

$$l_{max} = \alpha\,(15/2 * \varepsilon)^{1/4} / (\omega R_0 C_0)^{1/2} \tag{5}$$

with α being a coefficient equals to 1 or 2 for single terminated or double terminated cable, respectively.

To illustrate this length restriction for low frequency parameters, we consider a numerical example based on the following typical parameters:

- ε of 2%
- Measuring frequency of 12.5 Hz
- A single terminated cable with a nominal loop resistance R_0 and mutual capacitance C_0 of 190 Ω and 45 nF (typical values for cat cables), respectively.

Plugging these values into equation (5) leads to a maximum cable length of ~24 km. However, by simply increasing the frequency to 1 kHz, this maximum cable length reduces to 2.6 km only.

Hence, this cable length limitation needs to be known in order to properly interpret the measured low frequency parameters of twisted pair category cables.

3. Restrictions for High Frequency Parameters

3.1 Measurement Requirements and Challenges

Requested lengths from cable manufacturers to evaluate their cables vary from very short to very long. The ISO/IEC and TIA standards for twisted pair category cables (CatXx) define a testing length of 100m. Nevertheless, for Cat8 with majority of applications within the data centres, the standards set a length of 30m.

For automatic test equipment (ATE) systems, measurement of 30m and up to 100m cable length does not usually present any problems, given that certain precautions are taken as explained in the following paragraphs.

ATE's are split into two groups: balun-based and balunless systems. In the case of balun-based ATE, the system performance is strongly dependent on the return loss of the baluns, specifically when testing short cables. And this poses stringent requirements on the calibration method.

For balunless systems, cables can be very short, i.e. few meters only. Additionally, not being limited by the baluns opens the door to even broader frequency range over more than 4 decades. Nevertheless, it still requires special care in the system calibration. A dedicated calibration method or 'Short length testing' option can be provided by ATE manufacturers [4].

For longer cables like 305m or 500m (to measure a complete box or a drum for instance), a VNA (Vector Network Analyser) with an extended dynamic range is needed to overcome the increased insertion losses (IL) in the DUT.

But then, the following question arises: What is the needed dynamic range (NDR) and how to estimate it?

3.2 Needed Dynamic Range (NDR)

3.2.1 *System capabilities*

Usually the NDR that allows proper test measurements is directly related to the maximum attenuation (or Insertion Loss, IL) of the cable under test. However, due to the far-end crosstalk induced by adjacent cable pairs, ACR-F (Attenuation to Crosstalk Ratio – Far-End) must also be taken into consideration. ACR-F is a calculated parameter according to the following equation:

$$\text{ACR-F [dB]} = \text{FEXT} - \text{IL} \qquad (6)$$

This equation is meaningful only if you can measure IL and FEXT over the full frequency range of interest, and ACR-F remains positive, i.e. FEXT>IL. This sets the limit for the NDR, which can be expressed as follows:

$$\text{NDR [dB]} \geq \text{IL} + \text{ACR-F}_{\text{margin}} \qquad (7)$$

Typical IL and ACR-F values for CatXx cables are given in Tables 1-2 below (from [5]).

Table 1: Maximum IL requirements (According to IEC 61156-5)

IL [dB]	100m	305m	500m
Cat5e (@ 100MHz)	22.0	67.1	110.0
Cat6 (@ 250MHz)	32.8	100.0	164.0
Cat6$_A$ (@ 500MHz)	45.3	138.2	226.5

Table 2: Maximum ACR-F requirements (According IEC 61156-5, length scaling: IEC 61156-1)

ACR-F [dB]	100m	305m	500m
Cat5e (@ 100MHz)	23.8	19.0	16.8
Cat6 (@ 250MHz)	19.8	15.0	12.8
Cat6$_A$ (@ 500MHz)	13.8	9.0	6.8

Then, per equation (7), NDR is easily derived and shown in Table 3.

Table 3: Needed Dynamic Range (NDR)

NDR [dB]	100m	305m	500m
Cat5e (@ 100MHz)	45.8	86.1	126.8
Cat6 (@ 250MHz)	52.6	115.0	176.8
Cat6$_A$ (@ 500MHz)	59.1	147.2	233.3

The NDR defines the minimum requirements. However, your ATE capability is not solely limited by the VNA but is further degraded by the internal connectors, RF cables and switches, and if in place baluns, etc.…. Hence, you must also include system margin and noise as expressed in the below equation:

$$\text{ATE capability [dB]} = \text{VNA dynamic range} - \text{system margin} - \text{noise distance} \qquad (8)$$

In the following sub-sections and for illustration purposes, we perform the calculation for the two VNA models from Keysight, E5061B [6] and E5080A [7], respectively. Any other mid- and/or high-end VNA will deliver similar results and thus, these two examples could be considered as guidelines of good practice.

3.2.2 *Case 1: Keysight E5061B*

Key measurement parameters are the following:

- IF bandwidth specification: 1Hz
- VNA dynamic range: 125dB;
- System margin: 10dB;

- Noise distance: 20dB

From equation (8), the ATE capability equals to:
125dB-10dB-20dB=95dB

This 95dB value will set the limit for system capability and thus, the maximum possible cable length. This is reported in Table 4 below, with the shaded area corresponding to system limitations, i.e. for cable length of 305m, only Cat5e could be tested and the system would be unable to measure 500m long cables.

Table 4: Higher accuracy for the measurement, lower requirements for the VNA

NDR [dB]	100m	305m	500m
Cat5e (@ 100MHz)	45.8	86.1	126.8
Cat6 (@ 250MHz)	52.6	115.0	176.8
Cat6$_A$ (@ 500MHz)	59.1	147.2	233.3

3.2.3 Case 2: Keysight E5080A

Key measurement parameters are the following:

- IF bandwidth specification: 1Hz
- VNA dynamic range: 145dB;
- System margin: 8dB;
- Noise distance: 10dB

From equation (8), the ATE capability equals to:
145dB-8dB-10dB=127dB

Similarly, this 127dB value will set the limit for system capability as reported in Table 5 below. In this configuration, for 500m long cable, only Cat5e could be tested.

Table 5. Lower accuracy for the measurement, higher requirements for the VNA

NDR [dB]	100m	305m	500m
Cat5e (@ 100MHz)	45.8	86.1	126.8
Cat6 (@ 250MHz)	52.6	115.0	176.8
Cat6$_A$ (@ 500MHz)	59.1	147.2	233.3

3.3 Other Limitations

3.3.1 Internal crosstalk of the ATE

Obviously, the above calculations are only achievable if the ATE provides a better internal crosstalk (or isolation) than what is required by the NDR. A system upgrade would require testing and improvement if weaknesses are found.

3.3.2 Measurement time

For a 100m cable the standard IF bandwidth is usually set at 1 kHz. In the 2 cases shown above, we used the smallest IF bandwidth of 1 Hz in order to get the best system performance.

However, reducing the IF bandwidth leads to an increase in the measurement time. In the case of Keysight E5080A VNA [7], it comes as no surprise that a reduction of ~10 in IF bandwidth results in a similar increasing factor in measurement time. For instance, a change in IF bandwidth from 1 kHz to 1 Hz will increase the measurement time from 195ms to 195sec (3min 15sec), respectively (and this for a 201 points setting).

3.3.3 Cable type and boxing process

Additionally the cable type has to be considered. U/UTP cables measured in boxes or on drums can show some increased crosstalk as the turns or ends can be very close to each other and additional coupling can occur which would not happen if the cable would be laid straight out on the floor. S/FTP will be less sensitive to coupling due to the intrinsic screening of the cable design.

The boxing and/or recoiling process can also cause issues in return loss by frequent sporadic mechanical stress. This would be seen by sharp peaks which would normally disappear after stretching cables out during installation, although not always.

4. Measurement beyond System Capability

4.1 Extrapolation Procedure

As illustrated in section 3, there are physical limitations to ATE and the range of measurements that can be performed for a given VNA dynamic range. Though, outside this restricted measuring range, theoretical extrapolation is feasible in order to obtain a feeling of cable performances and a rough evaluation of compliance to standards.[1]

As such, ATE manufacturers have developed software procedures to extrapolate IL, specifically in the case of long cables for which the test system does not permit measurement beyond a certain frequency range [4].

The procedure consists in performing the following 3 steps:

1. Measuring the cable IL up to the maximum frequency of interest
2. Extrapolating IL up to the max frequency
3. Normalize IL to 100m cable length

The extrapolation is based on the following well-known non-polynomial equation for IL:

$$IL = a*\mathrm{sqrt}(f) + b*f + c/\mathrm{sqrt}(f) \qquad (9)$$

where a, b, and c, are constant coefficients, representing:

- a: copper losses including skin effect
- b: dielectric losses related to the loss tangent
- c: mismatch losses related to impedance mismatch between the DUT and the test equipment at low frequencies

The values for these constants are category cables specific. They can be found in reference [8]. Not surprisingly, the main contribution comes from the “a” term linked to the copper losses at low frequencies and then the “b” term at very high frequencies.

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[1] Needless to say that intrinsically, extrapolating leads to approximations only and that ATE manufacturers would neither be liable for any claims nor warrant the obtained results.

4.2 Experimental Data

The 3 steps approach described in 4.1 is applied for a 180m Cat6$_A$ long cable. The corresponding IL curve is illustrated in Figure 1. As observed, once reached the ATE capability limit at ~600MHz for 80dB IL, the curve is becoming “noisy” and thus without any physical significance.

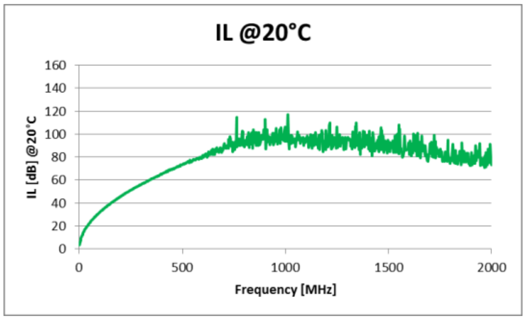

Figure 1: Measured IL for 180m long cable

The extrapolation step starts by fitting IL in Figure 1 over a frequency range for which the ATE capability is sufficient, i.e. up to ~600MHz, and then extrapolating using polynomial regressions. The result is shown in Figure 2, with the extrapolated part from 60dB onwards in blue-green dashes.

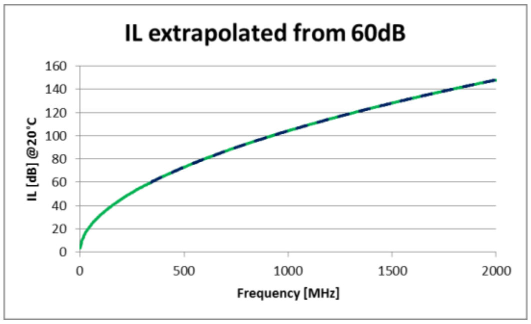

Figure 2: IL extrapolation from 60dB onwards (blue-green dashed line)

And at last, the normalization to 100m cable length, as shown in Figure 3.

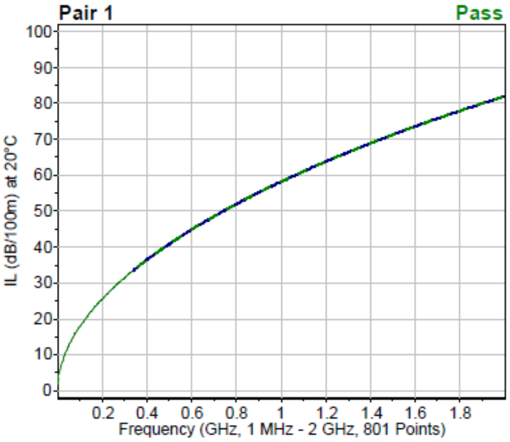

Figure 3: Extrapolated IL normalized to 100m

Similarly, this extrapolation procedure has been applied to the calculation of ACR-F. It is depicted in Figure 4 for the same 180m long cable.

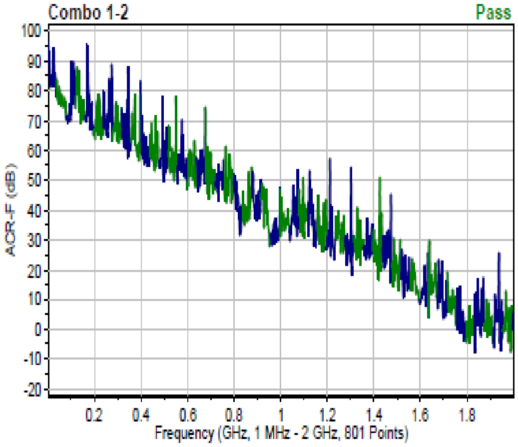

Figure 4: ACR-F after FEXT measurement and subtraction of extrapolated and normalized IL

As demonstrated, this procedure allows for an estimation of cable performance and as such, represents a fast approach to mass testing of boxes and/or drums for cable length beyond 100m. However, it does not in any means prevent for the need of frequent testing of standardised 100m long samples to ensure a high quality production according to standards.

5. Conclusions

Test measurement of cables to meet standard requirements is becoming a prerequisite. Although standards are dictating specific cable lengths per category types for testing, the production environment for multiple reasons does not always permit to meet these length constraints. But then, relevant measurements hinge on the technical mastering of your test system and test environment.

As highlighted in this paper, the cable length by itself can become a limitation, although this limitation can be overcome given certain experimental precautions.

For low frequency tests we can normally measure cables longer than 20 km, but this under some restrictions like conducting the measurement at the lowest frequency of 12.5Hz.

On the high frequency side, as no surprise, testing cables of 100m is always feasible. However, for cable length of 500m, only Cat5e cables can be tested. But this is achievable by using the lowest IF bandwidth at the expense of long measurement time. Although higher VNA dynamic range permits the testing of longer cable length, limitations come not only from the VNA itself but also from the noise level and system margin.

Higher category cables such as Cat7, Cat7$_A$ & Cat8, will be restricted to short lengths given that the needed dynamic range falls way beyond the ATE measurement capabilities.

Nevertheless, using a mathematical extrapolation and normalisation procedure for IL, it is feasible to guesstimate performances of long cables. Though, this procedure solely provides an assessment of the cable characteristics and does not prevent from the need for frequent testing of 100m long samples to meet compliance requirements for reporting.

6. Acknowledgments

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7. References

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8. Authors

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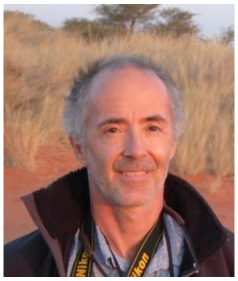

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