Length Restrictions in Cable Testing

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 length either shorter (50m or 30m for example for LAN cables) or longer (like 305m or 500m or even few kilometres for telephone cables). The reason to use different length could be economical to avoid too much wasting and/or an ease of process (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 Application Note (AN), 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 AN 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 Impedance, Attenuation/Insertion Loss, etc.. ; the last part describes the extrapolation procedure AESA has developed, along with and its intrinsic limitations.

1. RESTRICTIONS FOR LOW FREQUENCY PARAMETERS

When measuring long cable length with the Wheatstone bridge method, the risk is to lose the synchronisation 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], the input admittance of a cable is defined as:

$$Y_{In} = Y_C \cdot tanh(\gamma \cdot l) \quad (1)$$

With:

$Y_c = \sqrt{Y_0/Z_0}$	Characteristic admittance
$\gamma = \sqrt{Z_0 \cdot Y_0}$	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
l:	Cable length
R_0:	Nominal loop resistance of the line
L_0:	Nominal inductance of the line
C_0:	Nominal mutual capacitance of the line
G_0:	Nominal conductance of the line
$\omega = 2 \cdot \pi \cdot f$	Angular frequency

Developing the hyperbolic tangent in Taylor series we obtain:

$$Y_{In} = Y_c \cdot (\gamma \cdot l) \cdot [1 - \frac{1}{3}(\gamma \cdot l)^2 + \frac{2}{15}(\gamma \cdot l)^4 - \frac{17}{317}(\gamma \cdot l)^6 + \cdots] \quad (2)$$

Considering $\omega L_0 \ll R_0$ and $G_0 \cong 0$ (lossless transmission line), as a very good approximation for LAN cables, (2) can be re-written as follows:

$$Y_{In} = j\omega C_0 l \cdot [1 - \frac{1}{3} j\omega R_0 C_0 l^2 - \frac{2}{15}(\omega R_0 C_0)^2 l^4 + \cdots] \quad (3)$$

Given that the Automatic Test Equipment (ATE) only measures the imaginary part of the admittance and neglecting higher order terms in (3), the admittance simplifies as:

$$Im(Y_{In}) \cong \omega C_0 l \cdot [1 - \frac{2}{15}(\omega R_0 C_0)^2 l^4] = \omega C_0 l(1 + \varepsilon) \quad (4)$$

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

From (4) the formula used in our software to automatically calculate the maximum cable length dependant frequency value as function of ε is the following:

$$l_{max} = \alpha \cdot \frac{\sqrt[4]{\frac{15}{2} \cdot \varepsilon}}{\sqrt{\omega R_0 C_0}} \qquad (5)$$

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

For example:
For $f = {}^{\omega}/_{2\pi} = 12.5Hz$ (which is the standard for our AESA low frequency measuring units), $R_0 = 190\Omega$, $C_0 = 45nF$, $\alpha = 1$ (single termination), and ε=2%, we obtain a maximum length of: $l_{max} = 24km$.

For the same cable at $f = 1000Hz$, we would obtain a maximum length of $l_{max} = 2.6km$ only.

2. RESTRICTIONS FOR HIGH FREQUENCY PARAMETERS

2.1. MEASUREMENT REQUIREMENTS AND CHALLENGES

Requested lengths from cable manufacturers to evaluate their cables vary from very short to very long. The standards for category cables (CatXx) define a testing length of 100m. However, for Cat8 with majority of applications within the data centres, the standards set a length of 30m.
For AESA ATE systems, measurement of 30m and up to 100m cable length does not present any problems, given certain precautions as explained in the following paragraphs.

As cables get shorter, the performance for standard balun-based systems (e.g. Vega) is strongly related to the return loss of the baluns. This poses stringent requirements on the calibration method.
For balunless systems (e.g. Cobalt), 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, this is solely achievable with a specifically designed calibration method.
This specific calibration method or 'Short length testing' option on AESA ATE's can be provided as a software update for existing and/or new systems.

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

But then the main question is: what is the needed dynamic range (NDR) and how to estimate it?

2.2. NEEDED DYNAMIC RANGE (NDR)

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 considered. ACR-F is a calculated parameter according to the following equation:

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

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

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

Typical IL and ACR-F values for CatXx cables are given in Table 1-2 below (from 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 1: Maximum IL requirements (According to IEC 61156-5)

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

Table 2: Minimal ACR-F requirements (According to IEC 61156-5)

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

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

Table 3: Needed Dynamic Range (NDR)

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

ATE capability [dB] = VNA dynamic range - system margin - noise distance (8)

In the following, we perform the calculation for the E5061B and the E5080A VNA from Keysight. Any other mid- and high-end VNA will deliver similar results and thus, these two examples must be considered as guidelines.

i) Case 1: E5061B

IF bandwidth specification: 1Hz
VNA dynamic range: 125dB;
System margin: 10dB;
Noise distance: 20dB

→*ATE capability*=125dB-10dB-20dB=95dB

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

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

The shaded cells correspond to the region where the ATE will no longer be able to do measurements, i.e. for cable length of 305m, only Cat5e can be tested and the system is unable to measure 500m long cables.

ii) Case 2: E5080A

IF bandwidth specification: 1Hz
VNA dynamic range: 145dB;
System margin: 8dB;
Noise distance: 10dB
→*ATE capability*=145dB-8dB-10dB=127dB

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

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

The shaded cells correspond to the region where the ATE will no longer be able to do measurements, i.e. for 500m long cables, only Cat5e can be tested.

2.3. OTHER LIMITATIONS

2.3.1. Internal crosstalk of the ATE

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.

2.3.2. Measurement time

For a 100m cable the standard IF bandwidth is 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 capability.
However, reducing the IF bandwidth leads to an increase in the measurement time. As shown in the table below in the case of Keysight E5080A VNA [2], 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 (this for a 201 points setting).

Condition: Frequency = 4 GHz, NOP = 201, system error correction: OFF

IF BW (Hz)	Cycle time (ms)	IF BW (Hz)	Cycle time (ms)	IF BW (Hz)	Cycle time (ms)	IF BW (Hz)	Cycle time (ms)
10	19299	100	1932	1000	195	10000	21
30	6434	300	645	3000	66	30000	7.6

Table 6: Cycle time versus IF bandwidth [2]

2.3.3. 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 and additional coupling can occur which would not happen if the cable would be straight laid out on the floor. S/FTP will be less sensitive to coupling due to the intrinsic screening of the cable design.
The boxing process or recoiling process can also cause issues in return loss by frequent sporadic mechanical stress. This can be seen by sharp peaks which normally disappear after stretching cables out during installation, although not always.

3. MEASUREMENTS BEYOND ATE SYSTEM CAPABILITY

As illustrated in the section 2, there are physical limitations to ATE and the range of measurements that can be done 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.
Needless to say that intrinsically, extrapolating leads to approximations only and that AESA is neither liable for any claims nor warrants the obtained results.

With the above clarifications, AESA has developed a software procedure to extrapolate IL, specifically in the case of long cables for which the ATE capability does not permit measurement beyond a certain frequency range.
The procedure consists in performing the 3 following steps:

1. Measuring the cable IL up to the max frequency of interest.
   The result is illustrated in Figure 1 for a 180m long cable. As you can observe, once you reach the ATE capability limit (~600MHz or ~80dB IL), the IL curve is becoming “noisy” and thus without any significance.

2. Extrapolating the IL up to the maximum frequency.
   The extrapolation starts by fitting the IL over a frequency range for which the ATE dynamic range is sufficient. The fitted IL is based on the algorithm described in the IEC standard [3]. Extrapolation is then done using polynomial regressions. The output is shown in Figure 2, with the extrapolated part from 60dB onwards in blue-green dashes.

3. Normalize IL to 100m long cable (see Figure 3).

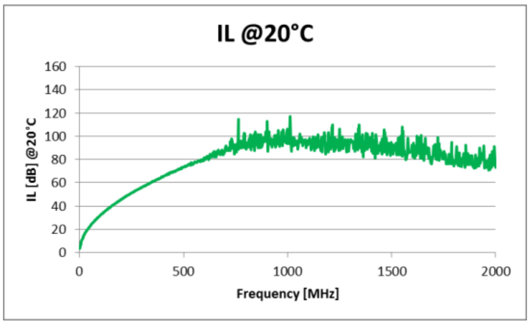

Figure 1: Measured IL of 180m long cable

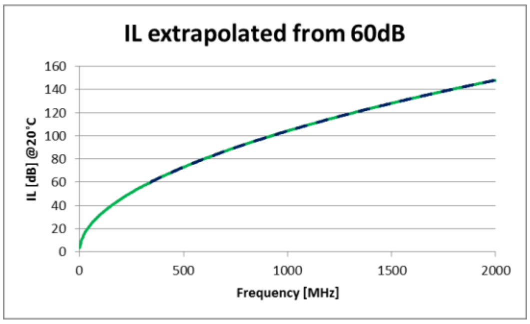

Figure 2: IL Extrapolation from 60dB onwards (blue-green dashed line)

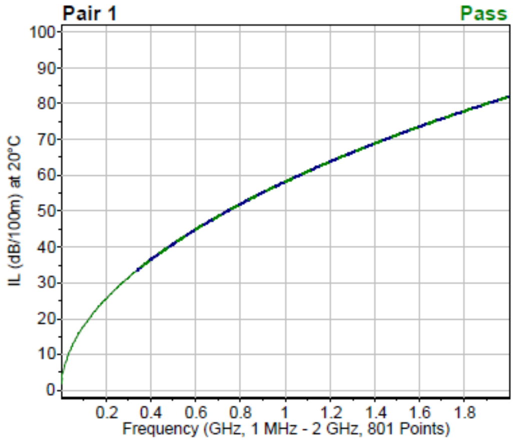

Figure 3: Extrapolated IL normalized to 100m

This extrapolation procedure has been applied to the calculation of ACR-F. Results are illustrated in Figure 4 for the same 180m long cable.

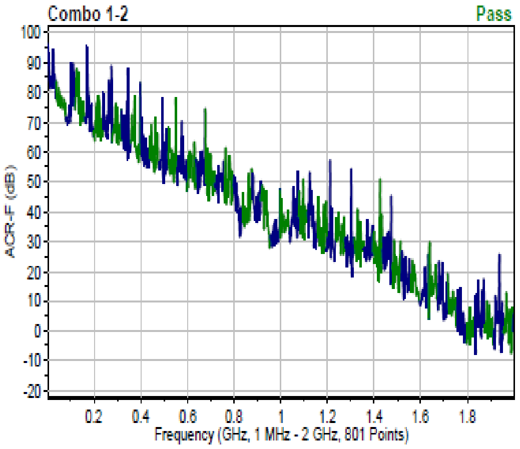

Figure 4: ACR-F after FEXT measurement and subtraction of extrapolated and normalized IL

This procedure allows for an estimation of cable performance and thus, represents a fast approach to mass testing of boxes and/or drums for cable length beyond 100m. However, as highlighted at the beginning of this section, it does not in any means replace the need for the frequent testing of standardized 100m long samples to ensure a high quality production.

4. CONCLUSION

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 feasible only 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 normalization 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.

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Bibliography

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[3] IEC 61156-5.