

Designing a Connection System for Gigabit Automotive Ethernet

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ABSTRACT

Ethernet technology using a single unshielded twisted pair (UTP) is considered to have a promising future in the automotive industry. While 100Mbps transmission speeds can be achieved with standard connector platforms, 1Gbps requires specific design rules in order to ensure error free transmissions. This paper explains the specific challenges for high speed UTP solutions applied in automotive environments. Automotive relevant signal integrity (SI) and electromagnetic compatibility (EMC) connector limitations are also discussed in detail. Through simulations and testing, the connector design criteria and rules necessary for meeting all the electrical and mechanical requirements for such automotive applications are evaluated and shown. This is followed by the introduction of a modular and scalable MATEnet Ethernet connection system utilizing an optimized cable termination technology. Lastly, the electrical performance of this hardware will be demonstrated with both component and link level testing results.

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INTRODUCTION

The architecture of in-vehicle networks is set to go through a transformation due to the rapid increase of camera, radar, and LiDAR (Light Detection and Ranging) based driver assistance systems, infotainment systems, high resolution displays, interactive navigation, and the integration of personal mobile devices. The draft IEEE standards for Automotive Ethernet utilizing 100Mbps [1] and 1Gbps [2] physical layers propose economically and performance promising technologies for such applications. While 100 Mbps data rate Ethernet technologies are already deployed in production cars today, the first 1Gbps links are expected to be introduced in the next few years. The annual global market is expected to surpass 100 million ports in passenger vehicles by the year 2020 [3].

Contrary to pre-existing Ethernet standards, the current development focuses on a brand new 1Gbps Ethernet physical layer (1000Base-T1) defined by the Institute of Electrical and Electronic Engineers (IEEE) in the ongoing project IEEE802.3bp [2]. The draft proposes the use of a single balanced copper cable of at least 15m in length as link segment (type "A"), for automotive applications. In order to meet automotive cost requirements, a single unshielded twisted pair (UTP) cable is being targeted. This is important to the automakers because the wiring harness is the third highest cost component in the vehicle; behind the engine and the chassis [4]. The cabling is also the third heaviest component in the car, and the use of lighter UTP could also help to increase fuel economy.

Implementing 1Gbps Ethernet in the automotive environment introduces design challenges. The 1000Base-T1 physical layer uses modulation schemes with frequency bandwidths up to 600MHz. Signals in this range have never been transmitted before on

unshielded cabling in this sensitive electromagnetic environment. The modeling of electromagnetic interference (EMI) in a cable harness and the definition of appropriate limits are required for these unshielded systems. However, the requirements of some components, including cable and connector limits, are not addressed in the IEEE standards. The link segment topology, including the electrical performance of the complete channel, is the only cabling hardware layer interface defined. Automotive connector platforms will also be required to meet other design challenges beyond those electrical performance rules. One major design objective is to define a small size modular solution where the core elements can be used for both 100Mbps and 1Gbps applications. Such a solution would reduce the variance and number of components required, yet still provide flexibility for specific connector constructions. Other automotive connector requirements regarding robustness, environmental stress, and vibration have to be met; including features such as locking, polarization and coding. Furthermore, the cable termination needs to provide high process-ability within the existing harness manufacturing ecosystems.

This paper begins by analyzing the SI and EMC performance of the unshielded 1Gbps transmission channel and proposes connector limits as a baseline for product development. Both electrical and mechanical design rules are then established for board headers and inline connectors. This is followed by the introduction of a modular and scalable MATEnet Ethernet connection system utilizing an optimized cable termination technology that meets these requirements. The electrical performance is then demonstrated by component and link level measurements on these connector prototype systems. Finally, conclusions are shown and optional future work is discussed.

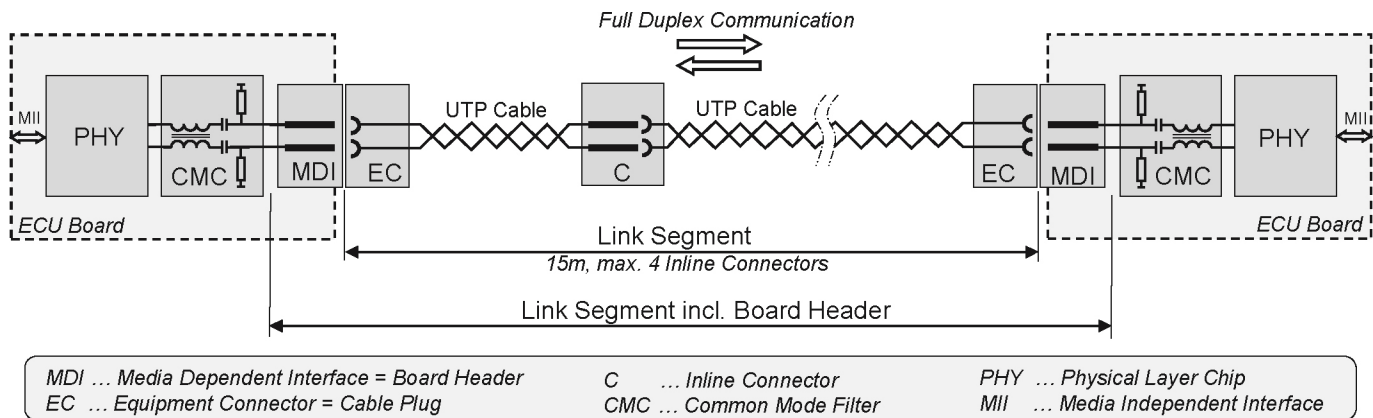


Figure 1. Type "A" Link segment topology as defined in IEEE802.3bp

LINK SEGMENT DEFINITION AND CONNECTOR PARAMETERS

Electrical Functionality and Topology of a Single Pair Gigabit Ethernet Link

The topology and definition of a 1Gbps Ethernet channel defined by the IEEE802.3bp draft is shown in [figure 1](#). The current draft suggests balanced signaling with 3B2T 3-level pulse amplitude modulation (PAM3). Including error correction and overhead, this results in a symbol rate of 750Mbaud and 375MHz frequency bandwidth to achieve the 1Gbps data rate. The maximum required frequency for the link segment definition in [2] is 600MHz to provide some design margin for the filter circuits.

Nominal differential mode (DM) impedance of the link segment is specified as 100 . For the DM signaling, the important parameters for signal integrity are insertion loss and return loss. The electromagnetic compatibility in an unshielded system is dominated by the common mode (CM) noise versus ground. The DC-free differential signal coupling to the PHY transceivers and additional common mode filter ensure immunity against CM disturbance from the environment and prevent emission of common mode noise from the PHY circuit. However, imbalances in the cable harness and connectors may cause conversion of common mode noise pulses into differential mode signals, which will not be rejected by the filter circuits. Therefore, the reflected and transmitted mode conversion values such as longitudinal conversion loss (LCL), longitudinal conversion transfer loss (LCTL), transverse conversion loss (TCL), and transverse conversion transfer loss (TCTL) should be taken into consideration. For multi-pair systems, the near and far end cross mode conversion to neighbor lines are also important EMI parameters in an unshielded system. Lastly, the differential near end and far end cross talk (NEXT & FEXT) to adjacent balanced data pairs is an additional disturbing noise source.

The IEEE draft considers these effects by limit definition for the cabling link segment. As depicted in [figure 1](#), the board headers are typically not included when specifying the link segment. However, in this study, the complete link from board to board, including the MDI headers, are included in order to allow direct measurement of mated connector parameters rather than separating plug and header values

by de-embedding techniques. The IEEE limits are applied to this extended link segment without degradation, which may add some amount of margin when calculating the budget for the connectors.

Signal Integrity Parameters

Insertion Loss

[Equation \(1\)](#) shows the insertion loss limit for the link segment as defined in [2]:

$$InsertionLoss_{Link} \leq 0.0023f + 0.5907\sqrt{f} + 0.0639/\sqrt{f} \text{ dB}$$

$$1 \leq f \leq 600, \text{ frequency } f \text{ in MHz}$$

(1)

This definition is based on the cable attenuation for 0.23mm² stranded wire cross section, 15m length and a maximum temperature of 125°C. It also considers 4 inline connectors with an insertion loss of $0.02\sqrt{f}$ for each one. Expression (2) suggests a tighter limit of this study for the mated connector insertion loss in order to be consistent with the limit definition for the 100Mbps automotive Ethernet specification [5] and to include some margin for the mated board headers on both sides.

$$InsertionLoss_{Conn} \leq 0.0085\sqrt{f} \text{ dB}$$

$$1 \leq f \leq 600, \text{ frequency } f \text{ in MHz}$$

(2)

The dependency on the frequency's square root is caused by the skin effect, which is the dominant reason for signal attenuation in typical automotive connector designs. The dielectric loss has only a minor contribution and can be neglected for the insertion loss limit model given in (2).

Return Loss

The Return Loss limit specified in [2] for the link segment illustrated in [Figure 1](#) is defined by [equation \(3\)](#) below:

$$ReturnLoss_{Link} \geq \begin{cases} 19 & 1 \leq f < 10 \\ 24 - 5 \log f & 10 \leq f < 40 \\ 16 & 40 \leq f < 130 \\ 37 - 10 \log f & 130 \leq f < 400 \\ 11 & 400 \leq f \leq 600 \end{cases} dB$$

$1 \leq f \leq 600$, frequency f in MHz

(3)

Worst case for return loss means a link topology with maximum number of impedance discontinuities, (e.g., inline connectors), and lowest attenuation of the reflected signals, (i.e., shortest segment length and use of cables with lowest insertion loss). Furthermore, the reflected signals from different sources will superpose each other if the propagation time between the discontinuities is equal, (i.e., same length for all segments). The impedance mismatch of connectors and different nominal cable impedances for the individual cable segments are considered as the main reason for return loss. The latter reason can easily happen if different cable types will be used in the same link or in the case of different environmental conditions at different locations of the same channel, (e.g., low temperature in the door and high temperature and different cable type in the cabin for a side mirror camera application). The worst case impedance mismatch in such a scenario would happen if the cable impedance alternates between minimum and maximum tolerance from segment to segment. Reflections caused by random effects within a cable segment or by other reasons, (e.g., bends or buckling), should be low compared to this min-max tolerance mismatch.

A first analysis without any connectors but different segment impedances is performed in order to identify the maximum tolerances for the cable impedance. Equation (4) is used to estimate the cable attenuation [6].

$$InsertionLoss_{Cable} = \left(\left(1 + 0.004^{\circ}C^{-1}(T - 20^{\circ}C) \right) \cdot 1.2 \frac{l}{100m} \times \left(1.82 \frac{\sqrt{0.258mm^2}}{\sqrt{A}} \sqrt{f} + 0.0091f + \frac{0.25}{\sqrt{f}} \right) \right) dB$$

$1 \leq f \leq 600$, frequency f in MHz

(4)

This expression is the base for calculating the cable constants in (1) with temperature T set to 125°C, length l set to 15m and the wire cross section A chosen with 0.23mm², which are the IEEE reference values for the maximum cable attenuation. Equation (5) shows a modification of (4) with cable length l as a variable parameter for the return loss modeling approach:

$$InsertionLoss_{Cable} = l \cdot \left(C1 \cdot \sqrt{f} + C2 \cdot f + \frac{C3}{\sqrt{f}} \right) dB/m$$

$1 \leq f \leq 600$, frequency f in MHz

(5)

The coefficients $C1$, $C2$ and $C3$ are determined for the thickest wire cross section in the application (0.35mm²) and for the lowest temperature (-40°C). Table 1 together with Figure 2 illustrate the cable insertion loss given in (5). An additional 10% margin is added (case 4), since measurements on real cables without a jacket show a lower attenuation as compared to the IEEE model.

Table 1. Coefficients for worst case return loss cable model

Case	T [°C]	A [mm ²]	C1 [1/√MHz]	C2 [1/MHz]	C3 [√MHz]
1	125	0.23	3.2850E-02	1.5506E-04	4.2600E-03
2	20	0.35	1.8753E-02	1.0920E-04	3.0000E-03
3	-40	0.35	1.4253E-02	8.2992E-05	2.2800E-03
4	-40	0.35	1.2827E-02	7.4693E-05	2.0520E-03

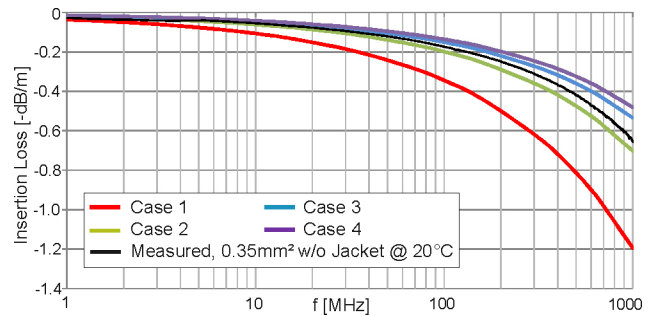
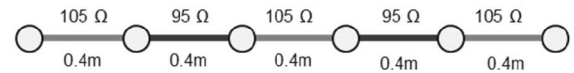


Figure 2. Cable insertion loss models for the return loss calculation

Continuing this analysis, figure 3 and figure 4 illustrate the worst case return loss, without connectors, for cable impedance tolerances of ± 5 and ± 3 utilizing the insertion loss model (case 4) from table I.

Cable Impedance $\pm 5 \Omega$:



Cable Impedance $\pm 3 \Omega$:

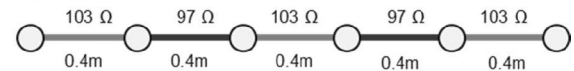


Figure 3. Worst case link topology w/o connectors

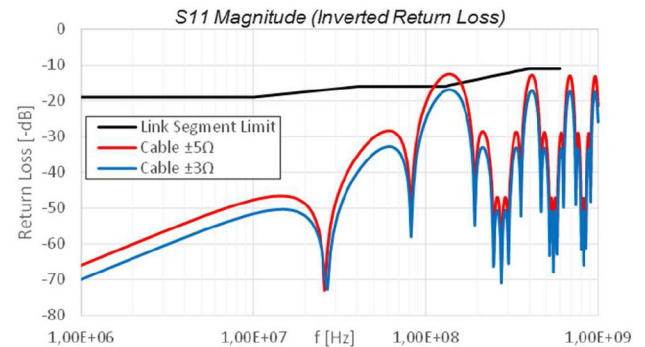


Figure 4. Cable only return loss for worst case link topologies

A maximum number of 5 cable segments with the identical length of 0.4m is chosen to move the first dominant return loss resonant peak to the region of 100~200MHz, where the link segment limit is more severe than at the higher frequencies. This is a reasonable assumption.

but more critical than typical topologies used in vehicles. The result of this analysis demonstrates that impedance mismatches between the cable segments larger than 6 ohms may exceed the link limit according to (3) even without any connectors.

The connector model for analyzing the return loss is a simple transmission line as shown in figure 5.

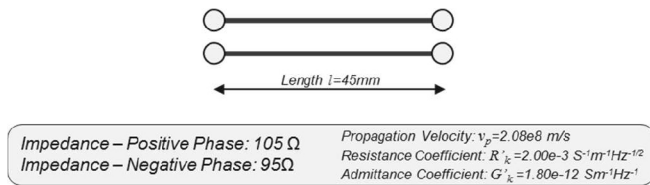


Figure 5. Connector model for simple transmission line

The Impedance values of 100Ω+/- 5Ω with a rise time of 350ps is chosen for the connector model. This is a best case scenario, and may be difficult to achieve in practice for all connector designs. This Impedance profile for both the 105Ω and the 95Ω connector models are shown in figure 6.

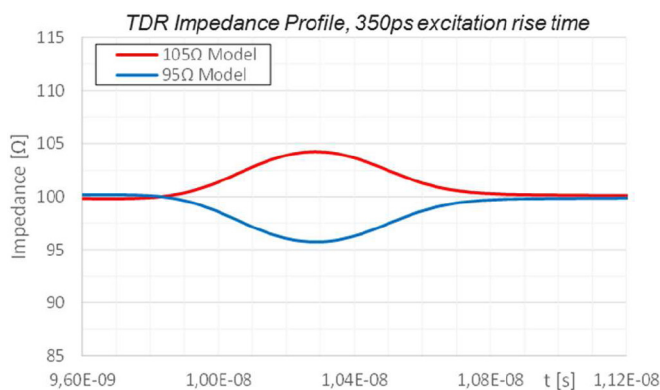


Figure 6. TDR impedance profile for connector models

The velocity and loss coefficients are obtained through analyses and determined to represent realistic values. The impedance values of 95Ω and 105Ω are determined to meet the link segment return loss limit in the worst case scenario as shown in equation (3). The return loss connector budget can then be defined by equation (6).

$$ReturnLoss_{Conn} \geq \begin{cases} 35 & 1 \leq f < 251 \\ 83 - 20\log(f) & 251 \leq f \leq 600 \end{cases} \text{ dB}$$

$$1 \leq f \leq 600, \text{ frequency } f \text{ in MHz}$$

(6)

Equation (6) can be considered an absolute worst case scenario, and may be reduced for practical purposes, given it defines a 16dB limit margin between the connectors and the complete link segment at 600MHz. The cut off frequency for values lower than -35dB in (6) is chosen to provide the same 16dB margin for the lower frequencies. Figure 7 shows the simulation results of the connector return loss.

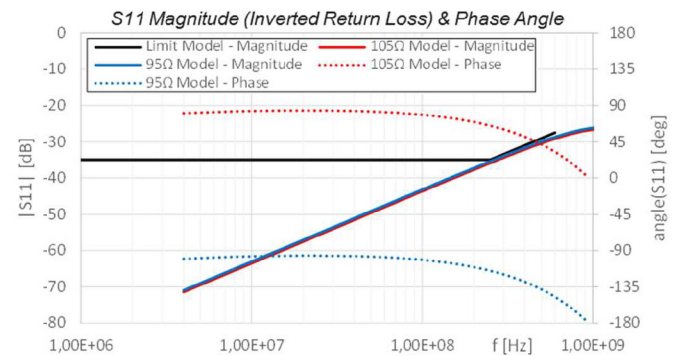


Figure 7. Simulation of connector only return loss

Finally, the complete link segment, including all connectors and cable segments is evaluated. The topology shown in figure 8 is used for the link segment simulation, which uses a maximum impedance mismatch of 10Ω between cable and connectors. The results of this worst case scenario is illustrated in figure 9.

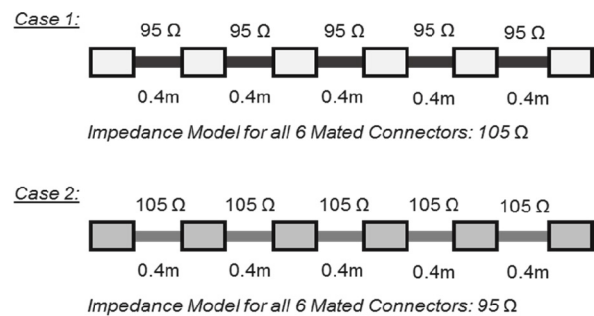


Figure 8. Worst case link topology with connectors

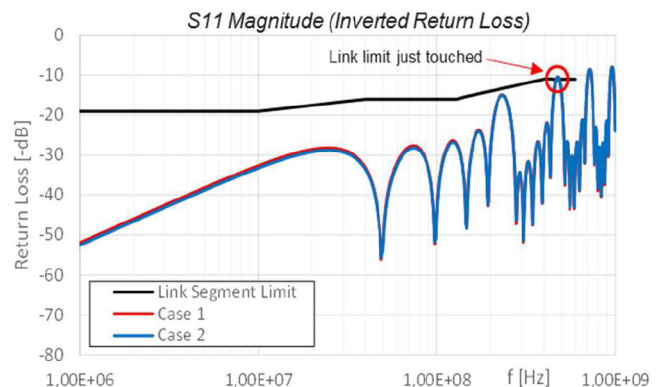


Figure 9. Complete link segment simulation results

These simulation results conclude that all mated connectors, including all inline couplers and board headers, require a return loss better than defined in (6). This corresponds to an impedance profile of 100 ± 5Ω at 350ps excitation rise time and connector length ≤ 45mm including total untwist wire length. The cable impedance tolerance shall also be at ±5% for all environmental conditions, and the mismatch in one channel cannot exceed 6Ω in total. However, in practically, it may be possible to relax these values since the described is a worst case scenario and is rather unlikely to occur in a real life implementation, (i.e., shortest cable segments of all equal length with minimum insertion loss and utilizing a maximum number of inline connectors).