Electromagnetic Compatibility in Connected and Electrified Vehicles

Extended Version

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Inhalt

1. Introduction – The Challenge of Growing Requirements

Modern cars are among the most complex networked electronic systems that exist. For years the number of electronic control units (ECUs) has continually increased, ranging between 70 and 100 ECUs per car, depending on the vehicle class. The resulting physical interconnection network, establishing the links between all these devices and with the next higher corresponding control layer has become very complex.

The amount of data that is transmitted via this network is also constantly increasing due, for example, to an ever-higher number of Advanced Driver Assistance Systems (ADAS) and comfort functions based on sensor data. The introduction of automation levels 2-3 within vehicles will increase significantly the share of so-called special links for high bandwidths. In the wider context of automated and autonomous driving (AD), RADAR, LIDAR and cameras will become essential to detect the environment. In addition to the continually increasing volumes and ever faster data flows within the vehicle, more data on the vehicle environment will be entering from outside the car via wireless and cellular technologies (4G/LTE, 5G; DSRC; C-ITS). This includes Cloud and Internet-based services, over-the-air (OTA) software updates, V2X and location services like eCall. Together they will dramatically increase the amount of data and the need to integrate antenna systems within the car.

Further complexity is created from a diverse and heterogeneous semiconductor landscape. Modern and high-performing systems-on-chip (SoC) have a design that facilitates millions of parallel operations which enables them to process mission-critical and safety-relevant information within one component. For an OEM this opens up completely new possibilities to design an electrical/electronic architecture (E/E architecture), as the physical layer (cabling) and the signal-processing layer (MII – Media Independent Interface) no longer need be split up into infotainment, safety and network domains.

Automotive Ethernet will soon be introduced globally

Automotive Ethernet will soon be introduced globally. During this process, modern SoCs will gain artificial intelligence enabling increasing levels of vehicle autonomy. This will result in new issues for connector developers and manufacturers when it comes to signal processing (shown as I/O). Essentially, the design of a vehicle network follows the factors presented in *Figure 1.*

Among the camera protocols MIPI CSI-2 is highly favored, as it can support up to 4 lanes with 4.5 Gbps as required by the latest camera resolution levels (4K to 8K), appropriate frame rates (~ 60 fps) and color depth (up to 24 bit) through new D-PHY version standards.

Current development projects are already taking up to 12 Gbps as a basis. The number of switches is gradually decreasing with the arrival of digital dashboards that integrate functions into touch panels. Displays with a mid-level resolution will continue to use LVDS as this only requires a moderate amount of implementation effort

Applications with a higher resolution, however, will bring about a shift towards (e)DP and HDMI. Including everything beyond multimedia applications, a total of up to 10 displays or

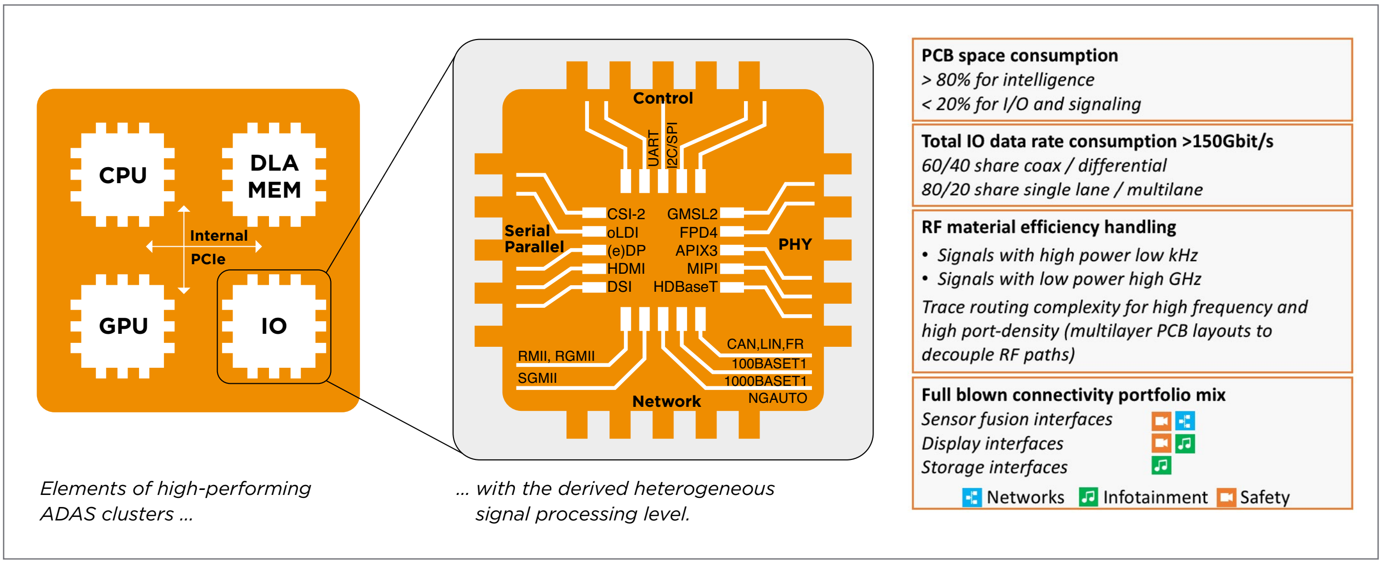

Fig. 1: Elements of high-performing computers and the heterogeneous signal processing that results from them

more is expected. For physical layer (PHY) solutions, the various automotive applications markets have long been guided by consumer standards and requires detailed high-speed expertise for every design-in. The semiconductor market as a whole has a key influence on future wire harness specifications. With complex modules such as core ADAS clusters, expectations range up to 150 Gbps, split between as many as 30 ports.

To establish chip-to-chip interconnections within a device, protocols such as PCIe are taken as the basis today. Future complex and fast algorithms will require ultra-fast data links.

A decision on the suitable/successful PHY technology for this is expected between 2022 to 2024. *Figure 2* provides an example with a focus on high-speed links.

2. EMC and TE's End-to-End Engineering Approach

Vehicle electrification adds another angle and challenge to the factors listed above. While the rising amount of data, with its high transmission frequency at low operating voltages requires an interference-free network, the high currents and voltages of an electric drivetrain create interfering fields that can turn into an additional influential variable for the

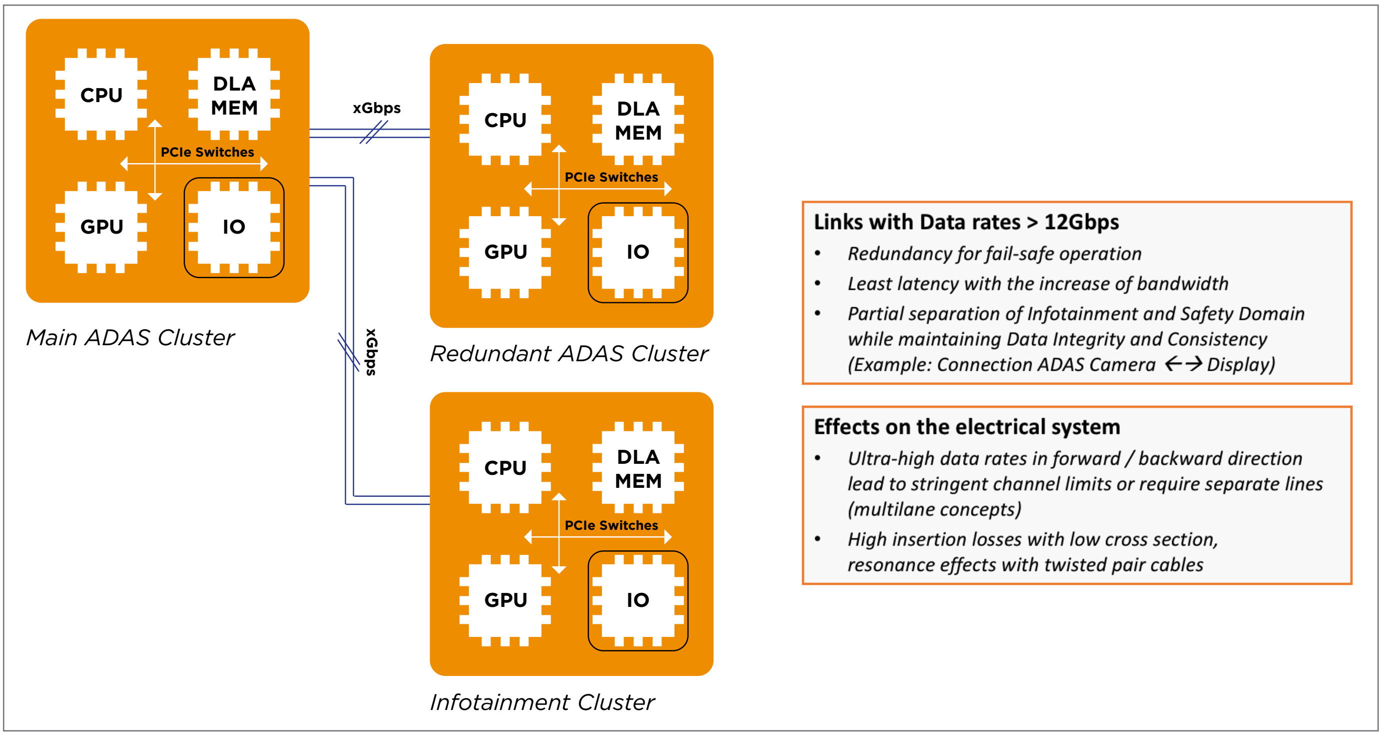

Fig. 2: High data rates of more than 10 Gbps will be especially required for high-resolution displays and automated driving

data links. To ensure that high-voltage electronics can coexist with fast data links, the high-voltage systems must fulfill the same specifications.

All of the components and devices (in the low voltage and in the high voltage field) which are relevant for Electromagnetic Compatibility (EMC) have to meet the applicable EMC standards in the vehicle to be fit for co-existence. Electromagnetic emission and electromagnetic susceptibility are regulated according to these standards through conductive and radiation-coupled testing. *Figure 3* illustrates TE Connectivity's (TE) role in the development of new interconnection systems.

It is an established practice that EMC requirements are designed-in from the beginning of the development for each new product. However, the channel specifications (also coming from standardizing bodies) continue to grow in significance. This is reflected in the left side of the above illustrated development lifecycle, while validation of interconnection systems, through testing, is found on the right side of the model.

As stated, as data gains significance within in the vehicle, the requirements for data transmission reliability also increase. This makes EMC a key focal point of development

This global trend means that EMC is becoming an an integral part of the complete development process. This paper shows how TE addresses and ensures EMC during component development using the example of an interconnection system designed for Automotive Ethernet. The focus is primarily on point-to-point connections for sensor data fusion and data transmission via the Ethernet network.

3. MATEnet Interconnection System for UTP/STP

3.1 Objective

Interconnection solutions for the Automotive Ethernet have to fulfill considerably stricter requirements on many levels than comparable termination solutions for stationary systems. In particular, the requirements span a much wider range of permissible ambient temperatures and the vibration resistance illustrate why only genuinely automotive-grade components, designed for this purpose, should be used in a vehicle. This will have even greater relevance when automated driving further increases the already stringent demands for robustness and reliability.

A further challenge for automotive-specific component development is to create economical solutions for such tough requirements. TE Connectivity's MATEnet interconnection system is one example. This

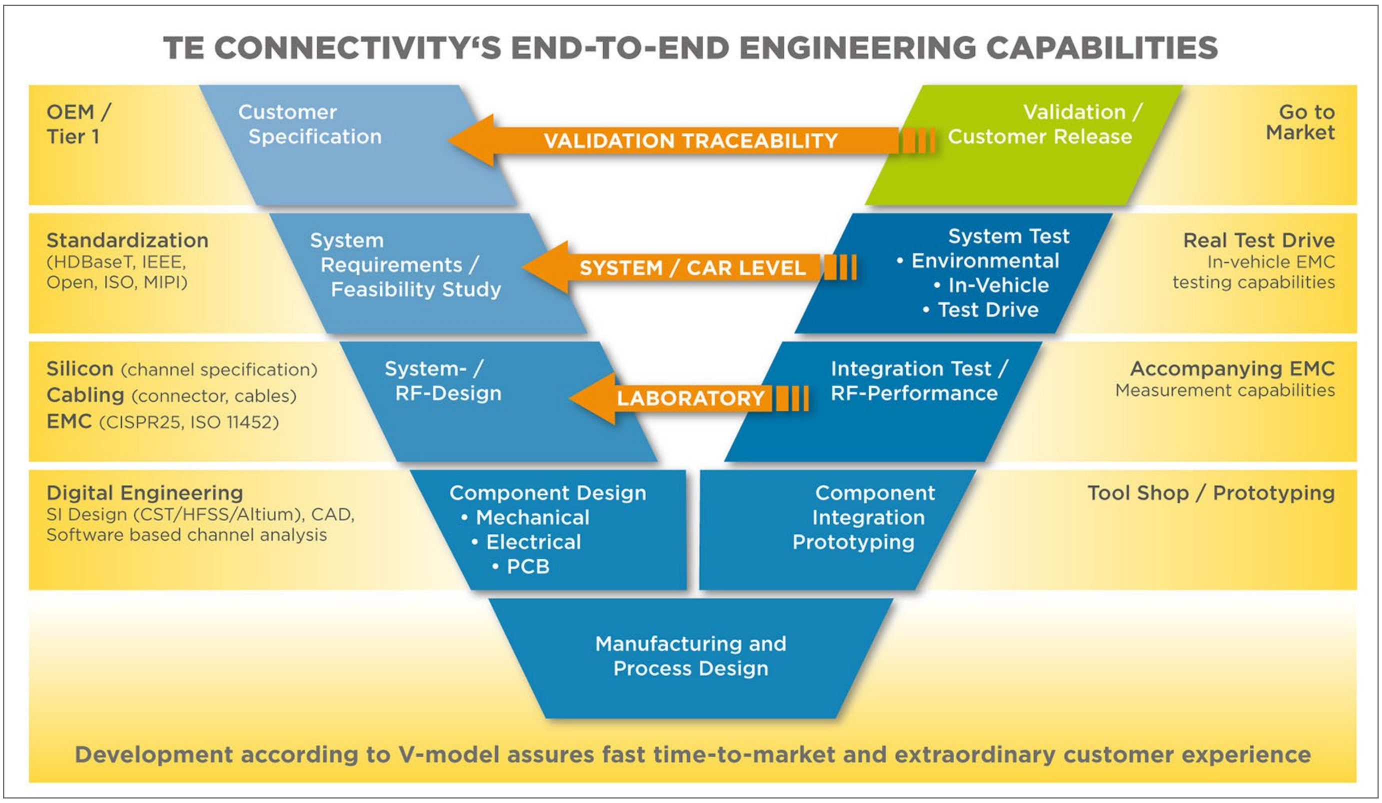

Fig. 3: The V-model mainly serves to speed up time-to-market

modular interconnection solution terminates the individual elements and links of a serial network based on the Ethernet standard.

MATEnet makes it possible to transmit intermediate amounts of data with moderate latency times via simple twisted cables of the Unshielded Twisted Pair (UTP) and Shielded Twisted Pair (STP) types. Automotive Ethernet based on UTP/STP is an economical solution which will continue to gain in importance.

3.2 Automotive Ethernet Today

The next Ethernet generation with transmission speeds of up to 1 Gbps is now ready for introduction into series projects. It expands the automotive network structure by adding another standard. Thanks to the early completion of the specifications defined by the IEEE working group 802.3bp in 2015, the OPEN Alliance committee was able to deliver an industrial standard which provides the basis for vehicle implementation.

The TC9 technical committee succeeded in putting together the specifications for using unshielded twisted cables (UTP) in vehicle networks. Currently an extension, adding shielded cables (STP), is under way and a result is expected in the near future. Through an appropriate choice of semiconductor, common mode choke, connector, and cable, UTP links can already be approved.

3.3 MATEnet Design Overview

MATEnet is a comprehensive end-to-end interconnection platform, with many advantages. It is a modular and scalable system with a core module based on the standardized Nano-MQS terminal and housing which can be used in various configurations as a multiport or for a sealed/shielded application. A core benefit of MATEnet lies in the ability to terminate UTP and STP cables within a single connector system.

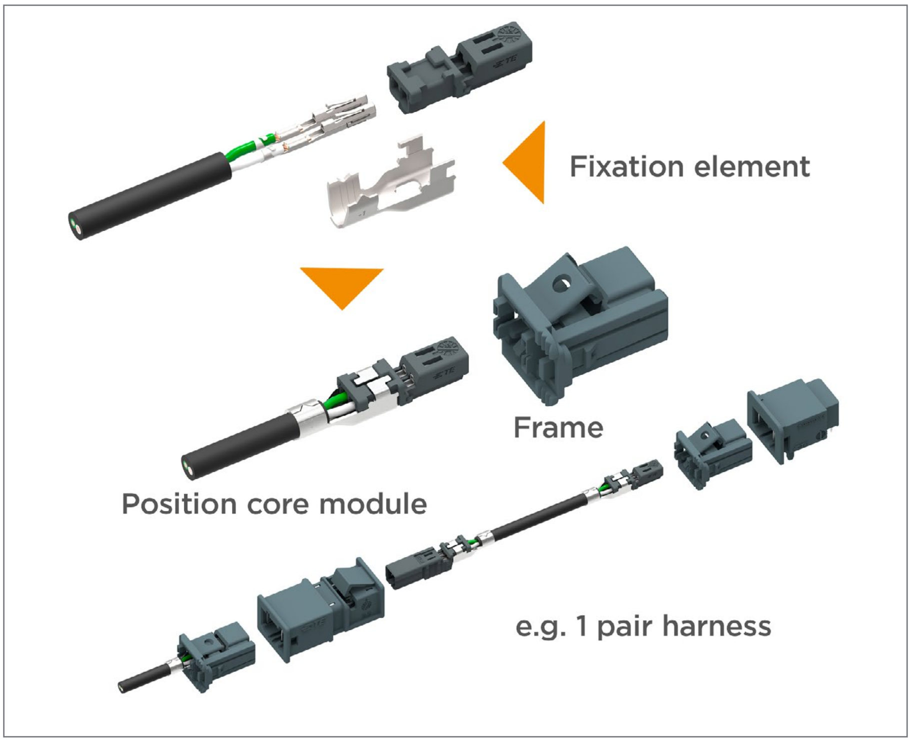

Fig. 4: The modular design of MATEnet

Figure 4 shows the components of the modular MATEnet system using the example of a 2-position interconnection.

The scalable product philosophy of MATEnet facilitates the termination of various cables with the same twisted-pair module. FIG. 5 illustrates the possibility to interchange an unshielded UTP termination (on the right in *Figure 5*) with a shielded STP option (on the left in *Figure 5*) – using with the same connector/header. This option to scale up or down makes it possible to change

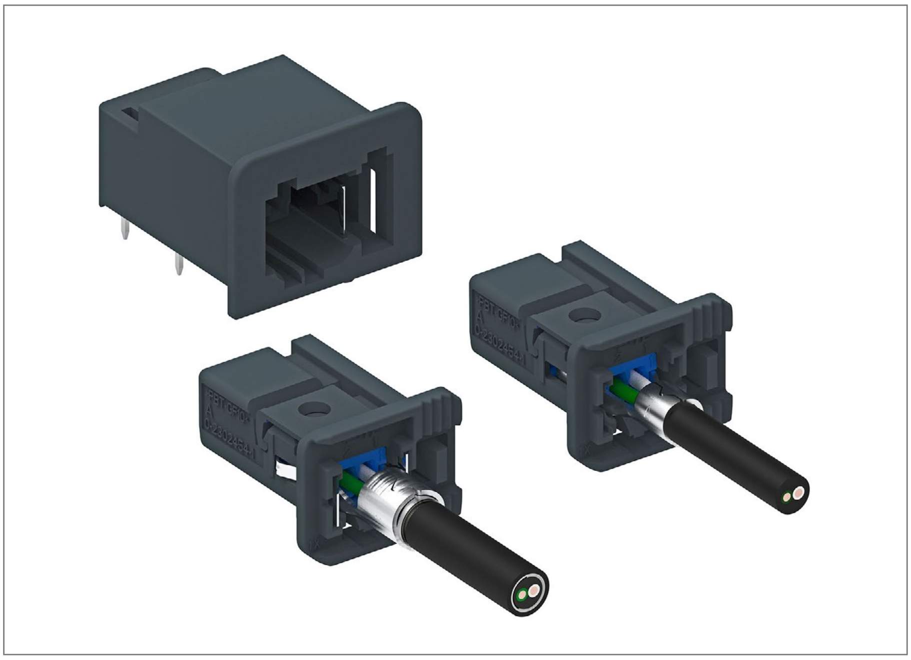

Fig. 5: Using MATEnet, STP cables (front left) and UTP cables (front right) can be terminated with the suitable frames without changing the header on the board

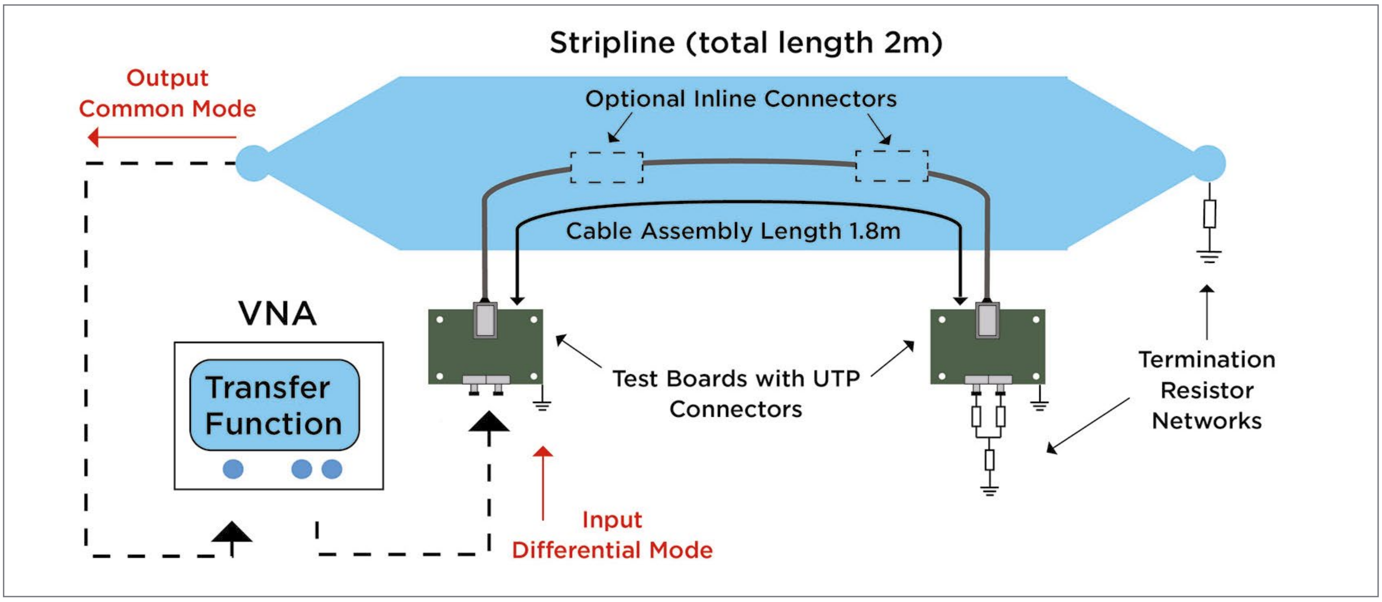

Fig. 6: Buildup of a stripline station as implemented in Neckartenzlingen

over to an EMC-optimized solution in a challenging environment without the need to make any costly changes to the device.

Tip: More detailed information on MATEnet can be found in the TE Connectivity White Paper [„Car Connectivity based on Automotive Ethernet".]

3.4. MATEnet – EMC Features and Properties

The MATEnet interconnection solution has fulfilled all relevant EMC tests (e.g. EMC according to CISPR25) and thus paves the way for cost-efficient introduction. Qualification and approval according to valid automotive standards have meanwhile been completed using series production products.

TE testing capabilities include measuring the shielding and coupling attenuation via the triaxial test method (measurement in the tube) at Bensheim, Germany as well as EMC measurements according to CISPR25 and radiated immunity measurements under ISO 11452 complete with electronics attached, performed in the TE testing facilities in Neckartenzlingen, Germany.

To characterize the EMC improvement, the unwanted common mode ("noise") at the output of the stripline can be quantified relative to the differential wanted signal in a transfer function, as depicted in *Figure 7*. Compared to UTP (1000BASE-T1 cable) a MATEnet STP solution can deliver a noise suppression which is an improvement of approximately 15 dB.

The high-balanced STP cable (Dacar 647-4 type) has an additional intermediate jacket which is located between the insulation of the wires and the shielding braid. TE has developed this cable together with a renowned cable specialist. Owing to the additional jacket, the cable shows properties which are more similar to that of a round cable than those of a twisted pair. Despite inevitable manufacturing tolerances that can be found in the insulation thickness following the extrusion of the wire insulation, the jacket ensures a specific minimal distance between the stranded wires and the shielding braid underneath the outer jacket. In contrast to conventional shielded cables with the shielding braid directly adjacent to the wire insulation, the high-balanced cable's mode conversion properties are improved by approximately 20 dB.

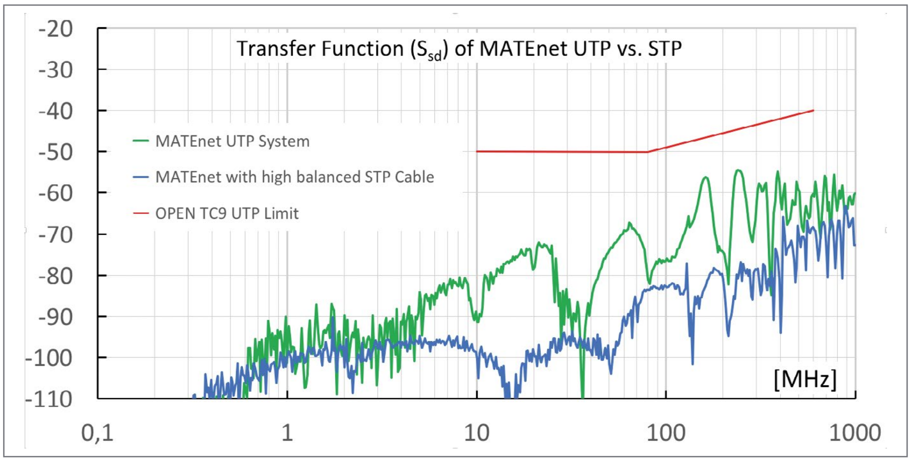

Fig. 7: Stripline coupling attenuation measurement of UTP (green curve) and special high-balanced STP cable (blue curve) in relation to the TC9 limit (red).

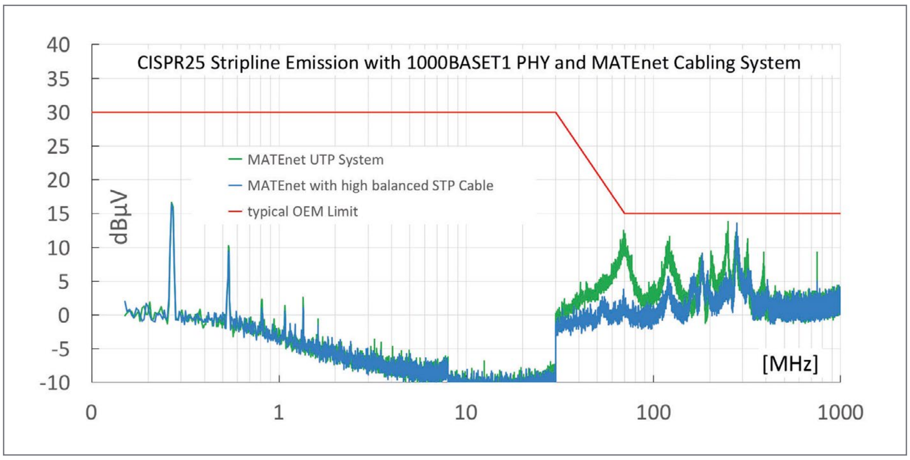

Fig. 8: Results of the stripline EMC measurement according to CISPR25 for UTP (green) and STP (blue) in relation to a representative OEM limit (red)

The relevant approval procedures on a system and ECU level are EMC measurements under CISPR25. In this context, the stripline measurement offers advantages over antenna measurement in the frequency band up to 1 GHz. Together with engineering services experts, TE was able to develop ECUs to demonstrate the improved EMC range. During this program the tests confirmed the expectations and an approval for unshielded and shielded MATEnet cabling could be given (*Figure 8*). In addition, the improved coupling attenuation could be clearly demonstrated.

The MATEnet STP frame is designed to provide an improved shielding efficiency. The termination of the cable shielding within the core module of the system is performed by additional metal shielding inserts via shielding contacts in the STP frame. This partial shielding concept utilizes the remaining common mode share being drained via the metal symmetry sheets in the header. Therefore, a partial shielding proved sufficient to meet the EMC standards with the shielded MATEnet by achieving a moderate EMC improvement in the relevant range. Looking at the EMC behavior in total (the permissible EMC level) from IC to IC (i.e. over the full length of the measured link) one can easily understand the complementing effect of the high-balanced cable and the shielding (*Figure 9*).

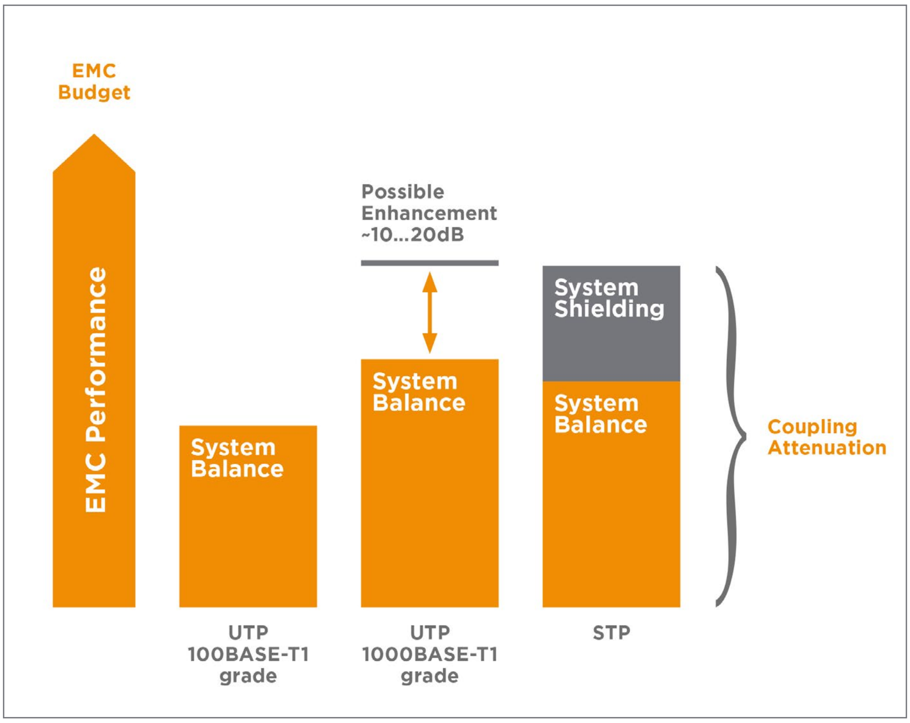

Fig. 9: Complementing benefits of the high-balanced cable and shielding

4. The MATE-AX Coaxial Interconnection System and its EMC Properties

In the vehicle coax cables are preferred over differential interconnections systems because coax cables are very compact and easy to wire. Though originally developed for transmitting analog signals in radio and antenna systems, they are now being used for digital point-to-point interconnections (high-speed lines) in infotainment and also for safety-critical applications, such as connecting ADAS cameras.

The preferred coax solution for this type of fast ADAS sensor are systems such as the miniaturized coax interconnection system MATE-AX because they offer the necessary bandwidth for transmitting raw camera data. Via a channel-based analysis it was possible to show the compatibility for data rates >10 Gbps. In addition a buffer for potentially even faster transmission could be identified. The increasing relevance of digital coax interconnection systems requires additional test parameters with EMC assuming a pivotal role.

4.1 Brief Introduction to the MATE-AX Design

MATE-AX is a miniaturized coax interconnection system for vehicle applications. MATE-AX is the result of detailed optimization work, to meet the challenging requirements of RF transmission. Among the main quality features of the receptacle terminal

Fig. 10: 90° MATE-AX header (left), 180° receptacle connector (center) and 180° pin connector (right)

is the welded contact box which ensures high robustness, the reduced stubbing potential that is owed to carefully designed chamfers to lead in the pin contact into the female terminal, and a design with the dielectric covering the conductor crimp of the inner terminal to provide short circuit protection. During the assembly of the connector, the terminal is fully inserted into the housing cavity which adds to the overstress protection level as lateral forces that could cause deflection are better absorbed by the cavity walls.

The MATE-AX receptacle terminal and pin terminal fit on existing RTK031 and RG174 coaxial cables. To terminate several camera signals as a physical first step of sensor fusion, miniaturized multi-port PCB headers establish themselves as a solution as they help save space in a central ECU. *Figure 10* provides examples from the MATE-AX portfolio. The figure also shows that MATE-AX terminals are very short in comparison to other products in the market. *Figure 11* summarizes core product features.

1) Pulse-amplitude modulation and innovative cabling can double the net rate, which facilitates 12 Gbps

Tip: For a more comprehensive background on MATE-AX please refer to the TE Connectivity White Paper „Miniaturized Automotive Coax Terminals".

Support broad application ranges including Network, Infotainment and Safety relevant functions
Long term support on high speed silicon products beyond 12 Gbps Superior RF and bandwidth capabilities (beyond 10 GHz) Full EMC compliance capabilities (CISPR25, ISO 11425) Successful compliance on a 6 Gbps NRZ coded PHY for ADAS purposes
Terminals fully protected in housing cavities High resistance against side pull High keying effectiveness (min. 130N depending on variant) Proven seal connector design
Shortes terminal in the market Consequent miniaturization (4x4 mm pitch) Full product offering: 180°, 90°, unsealed and sealed components Supports various cable types (RTK031, RG174)

Fig. 11: Overview of MATE-AX features

4.2 Coupling Mechanisms and the Triaxial Procedure in Relation to the MATE-AX System Design

To evaluate the EMC performance of a component or transmission link four different mechanism of coupling can be allocated to several areas of testing. *Figure 12* summarizes the parameters, which are relevant for automotive cable assemblies in the context of this paper. The middle branch in *Figure 12* (i.e. capacitive and inductive coupling), which applies to passive components, is taken care of by the connector manufacturer during component development, and this branch plays a key role especially with multiport applications.

To address the right branch (representing radiated coupling) shield attenuation can be measured with the triaxial procedure to facilitate an evaluation of the EMC performance (*Figure 13*). This serves to prepare the very sophisticated EMC measurement at the ECU level. In particular potential weak spots of a cabling system can be thus avoided.

The right branch in *Figure 12* can only be handled in a cooperation between the connector manufacturer and the OEM or IC maker during the development because testing in this phase includes the full electronics (ECU/IC) as in the installed state to ensure the correct function in the vehicle.

Electromagnetic emission is tested according to CISPR25, and electromagnetic immunity according to ISO 11452-2,4. In combination this means that for each link the performance of every component in the link plus the complete link are tested as a source and as a drain of electromagnetic interference.

The V-model (cf. *Figure 3*) shown at the beginning explains that meeting the component limits during the ear-

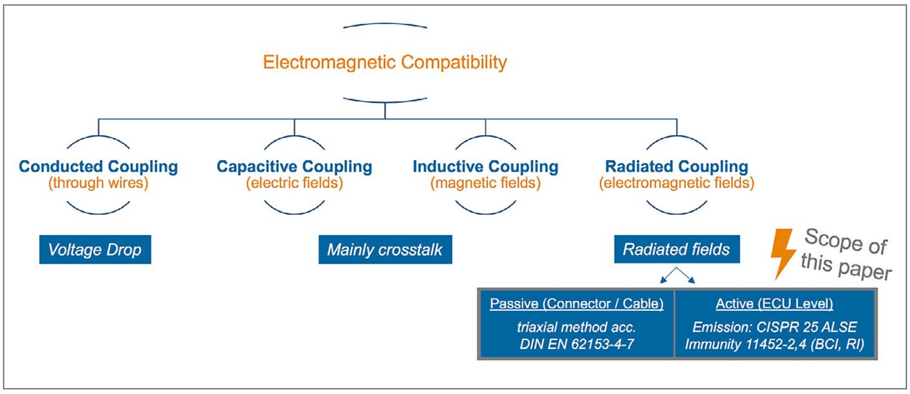

Fig. 12: The four coupling mechanisms of electromagnetic influences

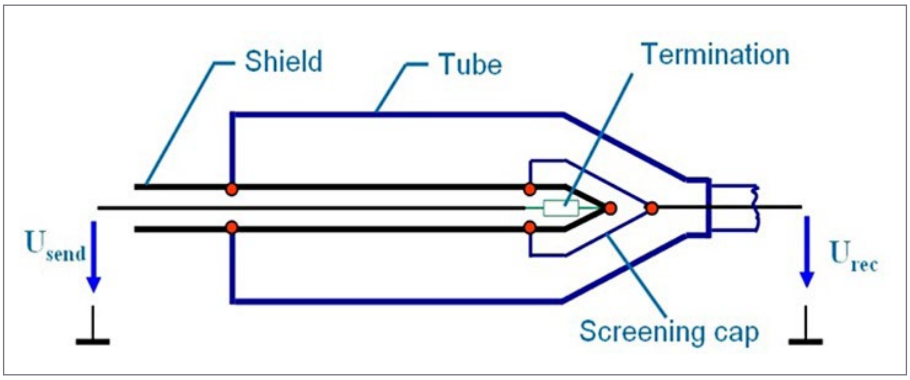

Fig. 13: Principle of the triaxial test procedure according to DIN EN 62153-4-7, as it is done in Bensheim

ly development phase provides the basis for meeting the OEM vehicle limits which are typically the result of long experience. This ensures the coexistence of all electromagnetic sources and drains which is the precondition for a correct function.

The correlation between EMC limits and the goal to ensure a correct function in the car is considered optimal when the component limits can be met in the tests according to CISPR25 / ISO 11452 on ECU level. However, to meet the ECU-level tests, shielding and coupling attenuation measurements serve to assess the EMC budget.

4.3 MATE-AX Design and Shield Effectiveness

The following results were measured with the MATE-AX terminal, which ensures a low-ohmic shield connection via a 360° shield and slots which are oriented towards the direction of the current flow (*Figure 14*). As the slots of the spring on the receptacle side are in line with the current flow, they are no obstacle to the current flow. The recess that is visible in *Figure 14* allows an automated camera-based checking of the correct terminal position in the assembled connector.

For comparative reasons two different types of cable were used during the shield effectiveness testing:

Figure 15 shows the different attenuation results for a coax line with a braided shield only (left) versus a high-performance cable with braid and foil shield /right). The different attenuation performance is easily explained. With low-frequency applications the low resistance between cable and shield sleeve makes the braided mesh the method of choice. With high-frequency (digital) applications like in the field addressed in this paper, however, the excellent shielding of the cohesive foil (i.e. an uninterrupted metal layer) against radiated coupling comes to fruition. At higher frequencies (which equal shorter wavelengths) the apertures of the braid will become permeable for radiation.

That is why the high-performance cable in *Figure 15* (right side) achieves a superior attenuation of around 80 dB in the relevant frequency band of 2 to 4 GHz while the standard cable with braided shield only does not show an attenuation better than a solid 50 dB in the same frequency band.

Clearly, it is necessary to use a high-performance cable in combination with a suitable connector design to meet the EMC limits. A typical use case helps to highlight this: If, for instance, an ADAS camera is installed in a side mirror and its signals are transmitted via a coax cable with just a braided shield, the mirror angle can influence the geometry of the braided shield via torsional forces, which can even increase electromagnetic radiation.

Fig. 14: MATE-AX pin terminal (top) and receptacle terminal (bottom)

4.4 Emission Results according to CISPR25 and Signal Integrity according to ISO 11452-4 (BCI - Bulk Current Injection) for an NRZ-coded Data Rate of 3 Gbit/s

As explained in the section on coupling mechanisms, CISPR25 is the relevant test to measure the EMI

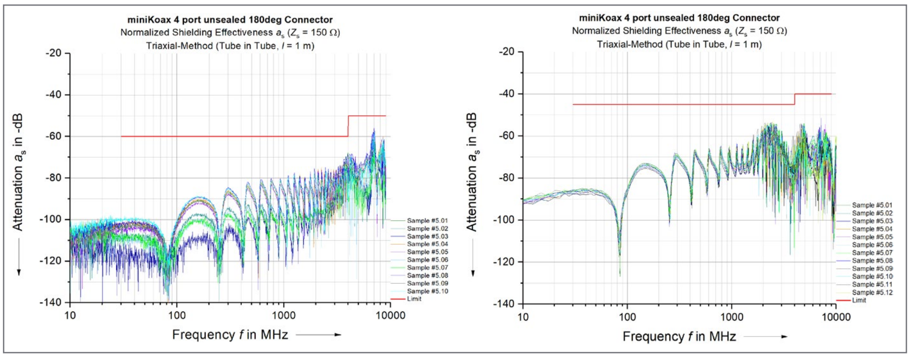

Fig. 15: Shield attenuation of an antenna cable with braided mesh only (left) vs. a high-performance cable with braid and foil designed for digital signals (right)

emission. The standard's valid version four, dating from 10-2016, contains comprehensive limit values which also cover requirements posed by drivetrain electrification. Interference severity level 5 contains the most demanding requirements to acceptable interference emission levels and was applied as limit to the measurement below.

To assess the data transmissions system's performance, the limits for broadcast and cell phone services are pivotal to ensure that such parallel services can work without mutual interferences. The figure below shows the influence of a housing shielding at the PHY (Board Level Shield, BLS) within an frequency band of up to 3 GHz. To highlight the results for the electronics, the test setting was changed in comparison to the standard setup by moving the antenna to the ECU position.

As the measurement in *figure 16* shows, all limits of severity level 5 could be met within the complete frequency band. This mirrors an excellent performance of the coaxial channel, with the possibility to further improve the coupling behavior by an additional (optional) shielding at the PHY.

For a production ECU with coax connectors it is quite important to ensure a suitable galvanic isolation (GND) from other potential coupling sources. As a conclusion one can see the excellent EMC performance.

For the sake of completeness, the measurement of RF immunity with a current clamp according to ISO 11452-4 (Bulk Current Injection, BCI) is also provided. During this procedure the signal quality was monitored visually via error-indicating LEDs. All relevant tests of this procedure with 200 mA of current were passed (cf. *Figure 17*).

Outlook

Current high-speed SerDes solutions, which are being implemented in the vehicle, focus on 3 Gbit/sec for HD-cameras with moderate frame rates and on high-end infotainment displays. In the case of cameras the required resolution and frame rates will go up to meet the needs of partial driving automation (e.g. 8 megapixels)

In the intermediate term this will lead to chip solutions for 6…12 Gbit. In the case of new display systems the higher resolution plus daisy chain architectures will result in higher data flows. TE is supporting chip manufacturers with EMC-relevant research to validate the technology side just as much as to validate additional tests, required for approval. In the very near future TE will conduct further tests and measurement on high-speed systems.

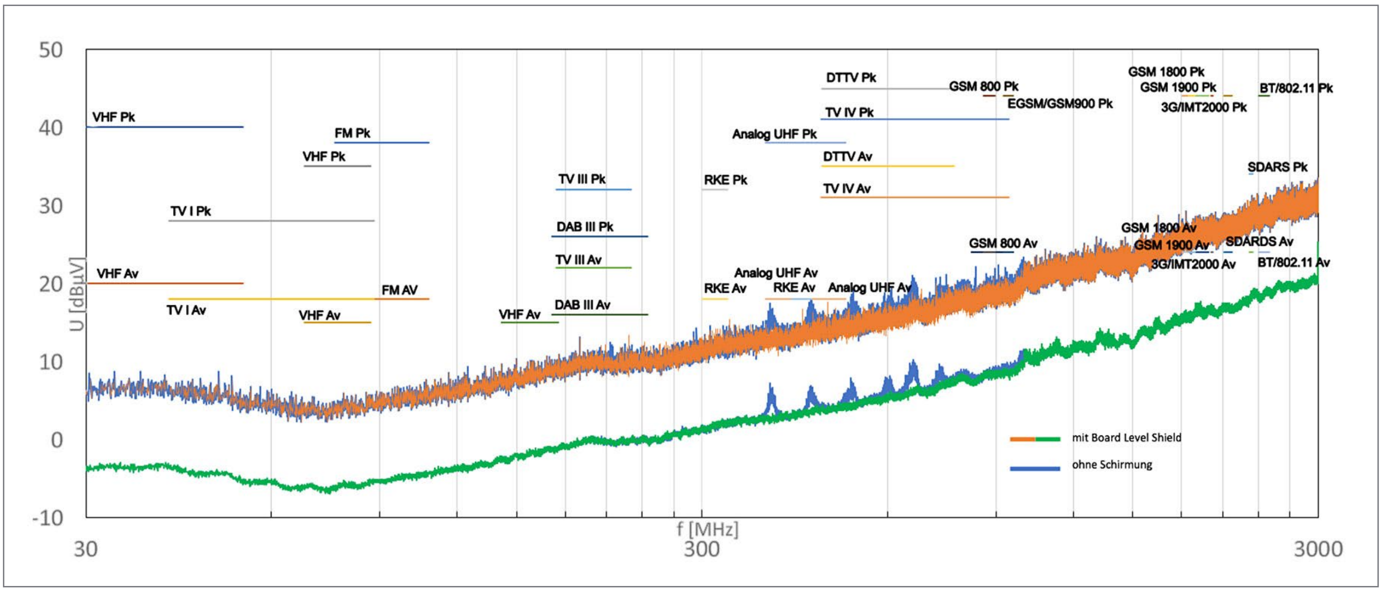

Fig. 16: CISPR25 test results – all limits of severity level 5 are met

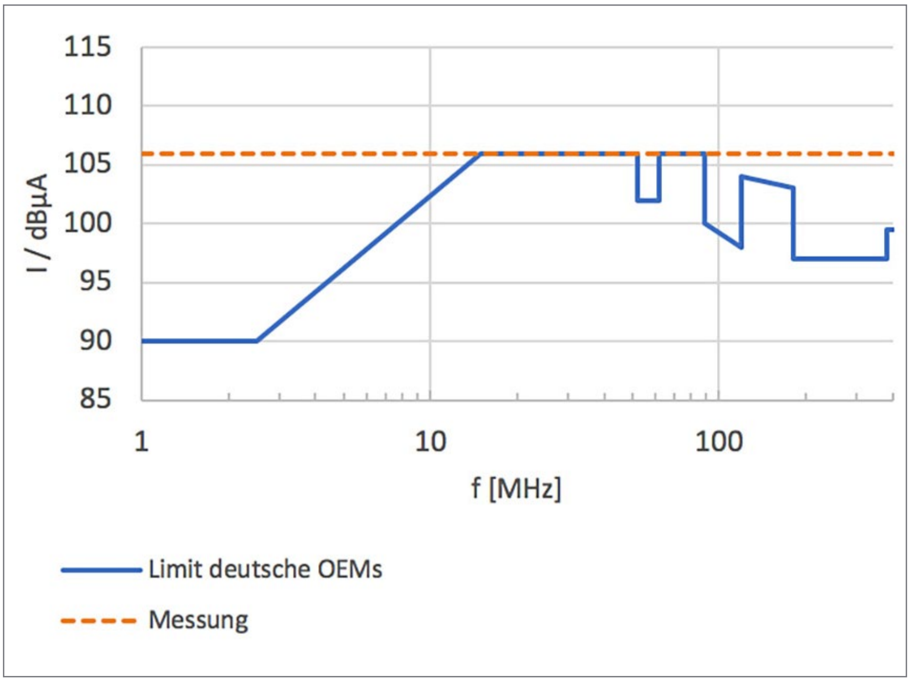

Fig. 17: Coax test results according to ISO 11452-4

5. Conclusion

Future automotive applications and the trend-setting shift to service-oriented architectures create more challenging requirements to network components in relation to modularity, scalability and bandwidth. In addition to higher transmission frequencies and larger amounts of data, high-voltage cables pose a challenge because all these elements of the physical layer have to coexist reliably and without interferences within the vehicle.

The development-accompanying optimization of the EMC behavior therefore also plays a role that should not be underestimated for connection systems.

TE is validating its automotive-grade interconnection solutions, such as MATEnet for Automotive Ethernet and MATE-AX for coax links, via comprehensive EMC testing. This enables them to fit seamlessly, safely and reliably into the existing and future networks of data and power lines. The performance features of the two interconnection systems discussed in this paper meet both the current and future requirements.

The unshielded MATEnet system for 100 Mbit and 1 Gbit was approved for use within the automotive network Ethernet by completing the qualification process according to valid automotive standards, under OPEN TC9 plus valid EMC standards such as CISPR25. As a result, the implementation of 100BASE-T1 and 1000BASE-T1 solutions in the vehicle can now be initiated.

The performance to meet the applicable EMC test standards for coax links was demonstrated by TE in July of 2019 by using a system based on a current chip. The MATE-AX design delivered excellent test results, which means that this type of robust automotive-grade coax interconnection system can be approved for vehicle use.

About TE Connectivity

TE Connectivity Ltd. (TE) is a $14 billion global technology and manufacturing leader creating a safer, sustainable, productive, and connected future. For more than 75 years, our connectivity and sensor solutions, proven in the harshest environments, have enabled advancements in transportation, industrial applications, medical technology, energy, data communications, and the home.

With 80,000 employees, including more than 8,000 engineers, working alongside customers in approximately 140 countries, TE ensures that EVERY CONNECTION COUNTS. Learn more at www.te.com and on LinkedIn, Facebook, WeChat and Twitter.

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