The challenge of future 10-Mbit/s in-vehicle networks

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Today's increasing demands on automotive system bandwidth cause a gap between well-established protocols like CAN and recently launched technologies such as 100BASE-T1 and 1000BASE-T1. To close this gab, system designers could choose one of three automotive protocols for 10-Mbit/s multi-node communication. While FlexRay is already available on the market, CAN-XL and 10BASE-T1S are currently under development, as they are still in the standardization phase. The basic question is the following: Which technology fits my system best? The answer given by the underlying analysis, with focus set on differences in protocol (data link), performance (physical layer), components and suitable in-vehicle network topologies, will help to take the right decision. General evaluations and comparisons are used to facilitate the correlation between a selected automotive use case and the reasonable communication protocol.

The number of electronic components and modules in new technical applications is increasing permanently. This leads to complex bus systems, especially in terms of comfort, multimedia, driver assistance, security functions, and automated driving. While the amount and need of data exchange will always rise, the permanent demand of minor costs and efficiency grows simultaneously. In order to fulfil both requirements, CAN XL and 10BASE T1S were developed as a convenient solution besides the rarely and reluctantly used 10 Mbit/s protocol FlexRay. This opens up the possibility to reduce complexity by reusing protocol layers of existing applications and avoids independent bus systems with individual characteristics.

Since the standardization phase of such new technologies is still not completed, there are a lot of open topics, issues and questions for all parties in the automotive industry. While Automotive Ethernet comes out with an exchangeable physical layer that facilitates the overall implementation and interaction of modules independent of the baud rate, CAN represents a well-known technology that brings a lot of advantages during the development phase and the introduction of an enhanced variant like CAN-XL.

Beside OEMs and Tier1s, especially semiconductor vendors are currently in a difficult situation. Smaller companies could not focus on both technologies and must decide regardless of unknown factors like future demand and positioning on the market. On the other hand, OEMs have not determined their final solution for upcoming applications and use cases in potential next car platforms.

All these uncertainties are based on the parallel development of 10BASE-T1S and CAN-XL, in combination with the cause and differences of all three candidates: While FlexRay is a time triggered protocol which was developed for the specific use case of 10-Mbit/s communication, both remaining protocols are lowered or raised according to their bandwidth. 10BASE-T1S initial comes from a point-to-point connection and faces the challenges of a multidrop link for the first time in the scope of Automotive Ethernet. The media access control differs from CSMA/CD method applied by CAN-XL and makes use of a method called PHY-level collision avoidance (PLCA). CAN-XL instead is an event driven protocol with arbitration and a fully revised physical layer.

For these basics alone, there may never be a collective consensus on the diverse controversy of whether one technology could cover all future application areas or not. At the end, it will depend on the requirements, layout and business strategy of the OEMs. The methodology of this wide-ranging study, however, provides the necessary room for maneuvers of developments that cannot always be precisely predicted several years in advance. It considers more than forty unique factors, that are used to compare and assess most significant characteristics and differences between the technologies. All applied factors are derived from ongoing discussions with semiconductor vendors, OEMs and over 20 years of experiences in the range of communication, testing and standardization work. They are rated as either informative or having an allocated multiplication factor that is used for a low-, mid- or high level of priority.

Significant factors are represented by the maximal latency, net data rate and payload, communication architecture and its real-time feasibility, wake-up capability, timeout handling, error detection and signaling, configuration parameters, applicable bus load, transceiver pins and needed components of the hardware interface, network design limits, bus signal frequency and power consumption. Further aspects are rated with a lower priority.

The general goal is to identify open tasks, accomplish a common understanding and simplify a first choice. The outcome serves as a benchmark for future applications and classifies all aspects into the following five main categories:

I. Availability

This category is based on the reliability of a system and the strategy of focusing on increasing testability, diagnostics and maintainability. The main emphases are given by a guaranteed communication after system startup, timeout handling, error detection and correction, bit error rate, time sensitivity and robustness.

To give an example, the error detection is split into two different aspects: First of all, the physical layer with its allowed glitches, signal quality indicator and further environment errors like shorted bus lines; secondly the data link layer with focus on the used cyclic redundancy check (CRC).

The Hamming Distance, that defines the minimum number of undetected bit errors, is rated as follows:

- FlexRay have a value of six for the header and a Hamming Distance of four by using a worst-case frame length.
- A 10BASE T1S frame have a Hamming Distance of four and is therefore in a worse position compared to FlexRay.
- CAN-XL comes out with a worst-case Hamming Distance of six, which is consequently the best obtained rating.

Since factors like the calculated bit error rate or the possibility to detect and identify specific error cases are more important, the Hamming Distance does not have a high priority and thus a low impact on the result.

II. Simplicity

The classification characterizes the complexity of the system and includes factors for bus access, the startup behavior with its synchronization and configuration effort of hardware, software and additional features. This category is directly linked to other parts of the analyses. The reason for this behavior is simple: To reach high effectiveness or availability, typically the complexity of a system increases at the same time. Thus, all three technologies are very close to each other and show a smaller total value compared to the remaining four categories. The biggest impact is given by the configuration effort of higher layers, which cannot be evaluated in current state of standardization.

III. Flexibility

This category is based on the adaptability of a system to meet customers' needs in an efficient and fast way. Besides the payload, prioritization and wake-up capabilities, the network design and handling with potential extensions representing the key factors.

IV. Cost efficiency

Overall costs of a system are, of course, one of the most important and significant categories for all involved parties. Starting with production of the silicon, the number and complexity of needed components in an electronic control unit (ECU), possible network layout types and licenses primary affect the development and maintenance costs. Furthermore, the required scope of testing, power consumption and used cable type were considered within this analysis.

V. Effectiveness

The capability of producing a desired result should be the goal of all technologies. In reality, however, this target shows huge differences, especially between FlexRay and both recently launched protocols. The focus in this last category is given by the data throughput, latency, bus signal frequency, real time capability, consistency and the applicable bus load.

To take one example: Due to a fixed cycle time, the latency in a FlexRay based system is very high in relation to the other contenders, although there is a certain deterministic behavior. The latency of CAN XL depends on the bus load and used priority IDs, as well as communication schedule. This leads to a non-deterministic system, which will not fit in some specific applications. 10BASE-T1S represents the best result with its deterministic behavior and improved latency. The bus access method PLCA avoids unnecessary transmit opportunities and only a short time between the messages is lost. Furthermore, a higher priority of one or even more electronic control units could be managed by allocating several transmit opportunities in one communication cycle.

Current situation of 10-Mbit/s IVN

In a first step, the recently published status of all three technologies was captured. In Figure 1, a higher value is related to a primary qualification of the corresponding category. To identify open topics of the standard, every undefined factor shows the lowest possible rating.

As a result of such a proceeding, the upcoming chart represents the final outcome of FlexRay, whereas CAN-XL and 10BASE T1S are highly underrated in terms of their potential and will reach a much better result due to the ongoing standardization of these two protocols. It is already evident, however, that in three of five categories FlexRay is not the preferred technology even in the current incomplete situation and lose its standing in flexibility, cost efficiency and effectiveness. A general coverage of all hypothetical 10-Mbit/s applications is therefore questionable.

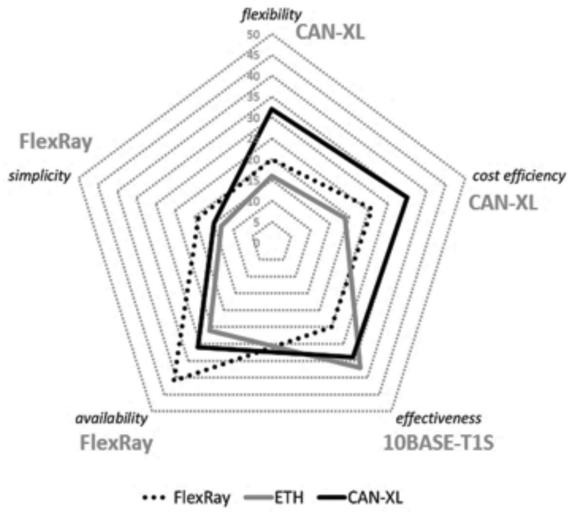

Figure 1: Current status

The highest value of availability is given by FlexRay, which can be explained by its time triggered communication and redundancy. CAN-XL clearly wins the categories flexibility and cost efficiency. This is caused by its flexible network design and baud rate. 10BASE-T1S currently shows the worst overall rating. The reason for that is given by the outstanding specification in IEEE and OPEN Alliance and not because of a restricted qualification of the technology.

The potential of 10-Mbit/s IVN

To archive maximal improvement potential, Table 1 provides essential efforts, that must be handled in IEEE, OPEN Alliance, and CAN in Automation. All these associations established working groups who take over the standardization task and who are already today defining and optimizing both standards. Given that FlexRay is defined in a very complex and accurate way, there is not much scope for potential updates or enhancements in the future and thus its characteristic remains the same.

Table 1: Specification and development effort to increase the potential

Category	Specification and development effort
Availability	- Error management definitions in OPEN TC14 and CiA 610 - Time sensitivity/-synchronization in IEEE, OPEN TC14 and CiA 610
Flexibility	- Wake-up / sleep standardization in OPEN TC10
Simplicity	- Wake-up / sleep standardization in OPEN TC10 - Configuration parameters are not fixed up to now
Cost efficiency	- SPI in OPEN TC6/TC14 and analog front-end specification in OPEN TC14 - Power consumption limits of the final devices

The upcoming figure is generated by using the maximal improvement potential, which is assumed by an approved and concluded standard, just as it is for FlexRay.

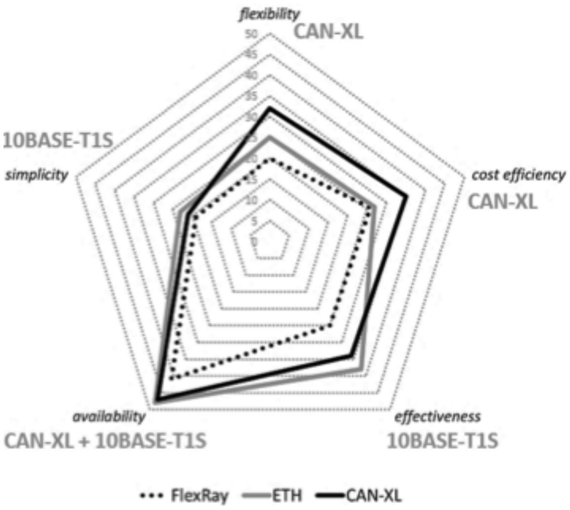

Figure 2: Prognosis

FlexRay does not show an advantage in any investigated category, if CAN-XL and 10BASE-T1S well complete the standards. They even show clear profiles with common dominance in availability. More than ever, it seems like one specific technology cannot cover all applications of future 10 Mbit/s in vehicle communication networks.

By comparing the current status with the potential of both technologies, there is still a significant effort necessary that requests a cooperation of all interested parties in this area. The goal should be a well-defined standard which facilitates the development, support interoperability between devices and drop the price as much as possible. Besides innovative solutions, the key to success is a joint and collective effort and the ability to think outside the box. CAN and Automotive Ethernet can learn from each other and both benefit from advantages and disadvantages made for FlexRay.

The layout of future 10-Mbit/s IVN

Today's trend shows a transition from the established domain controller architectures to upcoming zonal- and service-oriented architectures, which uses centralized compute units and instead of star wiring a backbone of zonal units.

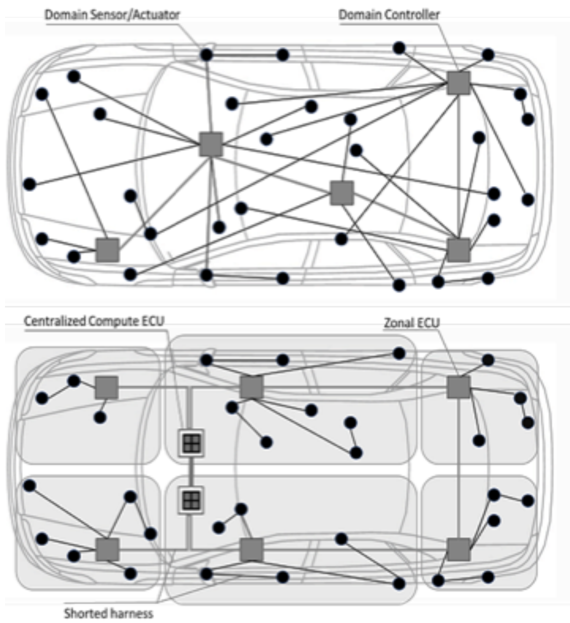

Figure 3: Today's architecture change

Sensor and actuator units of a zone are connected to the local zone unit, which requires only short wiring and support layouts with a kind of daisy chain structure. Nevertheless, a linear structure or network designs with star wiring are indispensable for several OEMs or, at least, can only be handled within the next evolutionary step of a vehicle platform. Due to this fact, in vehicle network simulations of the physical layer are conducted to point out the general differences between the technologies.

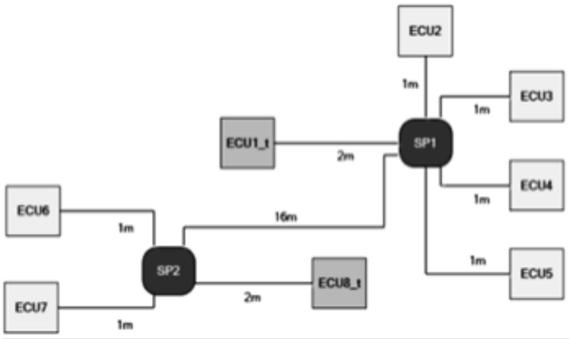

Figure 4: Network design of the physical layer simulation in time domain

The network design in Figure 4 is used for comparison only. It will typically not be used for all three technologies and does not meet the design requirements specified in IEEE for 10BASE-T1S. The results should be considered as fundamental research, since all previous analyses are only performed in frequency domain.

To trigger a worst-case condition, two star points and several equal stubs are used in the whole network. The total cable length is limited to minimal requirements specified for 10BASE-T1S. The standard itself defines a network with 10 cm stubs and the simulation therefore highly exceeds these limits. The generic driver modules for all three technologies are provided by an external co operational partner and partly supplemented by in-house developments. All of them covers the latest available version of the physical layer specification, including variations in corner case.

Simulation patterns were created to encode the data value 0x2800FFFF, to ensure stuff bit insertion at CAN-XL. The encoding overhead is given as follows:

- CAN-XL have two stuff bits. This number could be changed, because the stuff bit rule is currently not fixed in the standard.
- 10BASE-T1S have eight bits for 4B/5B encoding and its doubled number of bits for Differential Manchester Encoding.
- FlexRay have eight bits for its four bytes start sequence (two bits per data byte).

I. 10BASE-T1S

10BASE-T1S nodes which are far away from each other could reach its very low bus level just in time before the high signal frequency of 25 MHz forces a further state transition. The higher signal frequency results in a decreased network size. The following figure shows this scenario in detail. The channel definition and coding use voltage levels like CAN. Therefore, considerations shall be done in time domain what differs from other Automotive Ethernet standards that focuses only on frequency domain.

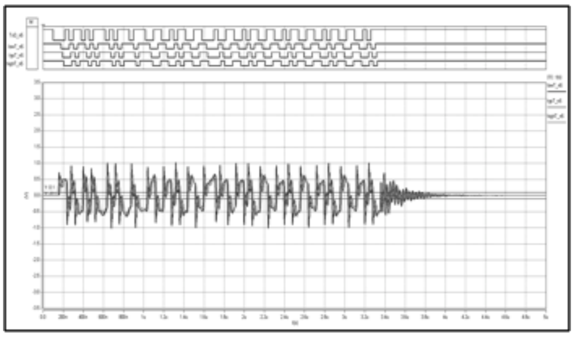

Figure 5: 10BASE-T1S simulation

II. FlexRay

Like it is shown below in Figure 6, FlexRay communication shows a disturbing analog ringing during the transition to IDLE. Such behavior is limiting the layout and is given due to missing technologies like devices with signal improvement capability.

Furthermore, the asymmetric behavior is the most limiting factor and additional active star points deterred OEMs by extra costs, evaluations and restricted network designs.

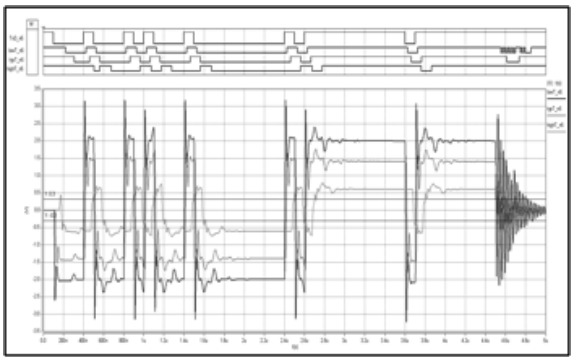

Figure 5: FlexRay simulation

III. CAN-XL

CAN-XL seems more suitable for larger networks, due to its higher signal-to-noise ratio, its flexibility in terms of scalability and the usage of the signal improvement implementations to avoid side effects like in FlexRay during the transition to IDLE.

Nevertheless, by using a baud rate of 10 Mbit/s a completely revised physical layer must be used without the well-known error signaling in the CAN-XL data field. This increases the complexity on higher layers. The potential risk of a long response time caused by an overloaded bus remains and is partly solved by using the optional feature of preemption. The physical layer will be updated soon and could show a different and, in some cases, worsened signal integrity as shown in Figure 6.

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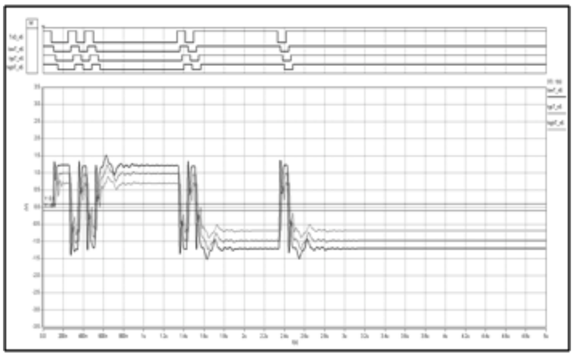

Figure 6: CAN-XL simulation

The mentioned subchapters show the signal integrity of each technology in one specific network. A further analysis covers the network layout type by means of point to point connection, daisy chain, linear bus and star point; the stub length of non-terminated nodes between 100 mm and 1000 mm and stub length of terminated nodes in various combinations; a main bus length between the terminated nodes from 5 m to 25 m and total number of nodes. It is shown that e.g. 10BASE-T1S networks could easily manage more than 8 nodes.

A step in the right direction, but…

The study only focuses on physical and partially the data link layer. In order to make an overall decision on choosing one of the discussed protocols, differences at higher layers must also be investigated depending on the given demands. They may have an influence on the outcomes this study provides. Total development costs or even the allocation of a user function and the associated need for communication signals within a whole network architecture are just two examples to be considered from the higher layer perspective.

The standardization work for 10BASE-T1S and CAN-XL must be completed, and individual application / use cases from the carmakers should be defined. Without such OEM-specific application / use cases, it is difficult to identify the right protocol which fits best. Furthermore, the prioritization within the shown categories could differ OEM by OEM. While some brands may concentrate on the cost efficiency, flexible network design and possibly fast ECU startup behavior of CAN XL, others may probably focus on an all IP car with its TSN and security potentials and reusability of the Ethernet software stack.

The given investigation, however, is a starting point prior to supporting the identification of an application profile for 10 Mbit/s communication and full validation of the networking architectures. It is used to point out difficulties, open tasks and topics which seem to be ignored or, at least, not being considered up to now. The former introduction of FlexRay and recent investigations for CAN-FD have shown that achieving a qualified signal integrity gets more challenging at increased baud rates. Effects like reflections, asymmetric behavior and HF / EMC influences limit the size of the network design and raises the complexity of the technology. Classic car architecture know-how gained over the years seems not to be fully applicable, especially for the upcoming protocols CAN XL and 10BASE-T1S. The setup and configuration of the overall system, design limits, validation criteria and testing approaches must be raised to a new advanced level to accommodate the use of 10-Mbit/s networking technologies in series car production.

Today's efforts ensure a step in the right direction, but there are several open issues to clarify and decisions to make in terms of standardization and use cases.

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