Introduction of CAN FD into the next generation of vehicle E/E architectures

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Automakers are about to introduce CAN FD into the next generation of vehicle E/E architectures. This paper will give an overview about general trends and technologies in the next generation of vehicle architectures. It will be shown how CAN FD fits into these new architectures and where, how and why it is used there. The way CAN FD interacts with other communication systems will be discussed. An insight into the everyday implications one has to deal with while integrating CAN FD from the architecture, software and hardware point of view will be given. Finally the paper will conclude with an outlook what to expect from CAN FD in future.

Introduction

In 1991 Mercedes-Benz launched the first CAN network in a passenger car (Mercedes S-Class series W140) with 5 CAN nodes and only one year later CAN was also deployed in a truck (Mercedes-Benz SK – "Schwere Klasse"). The first CAN applications enabled new concepts in the vehicles' powertrain and chassis domain. Soon CAN spread to all other domains of the vehicle, e.g. body, telematics and comfort. CAN was a key enabling technology that made driving safer, more comfortable and more efficient.

Figure 1: Vision of future mobility

Today automobile industry is on the verge of several dramatic changes in which four trends are standing out:

Connected driving: in future all vehicles will be connected online enabling amazing new services and applications – a revolution comparable the mobile phone industry when smartphones were introduced.

Autonomous driving: more and more driving assistance systems will be introduced finally leading to autonomously driving vehicles. This will also turn the dream of accident free driving into reality.

Shared vehicles: structural changes in urban areas but also in many peoples' societies suggest new usage and mobility concepts. These will be pushed by connected and autonomous driving technology.

Electric driving: saving our planet's climate, freeing megacities from pollution or a driving experience with unprecedented acceleration – there are many reasons why cars' powertrain will be more and more electric in future.

It is evident that these changes have a strong and demanding impact on future vehicle E/E architectures and on in vehicle networking technology. In the following it will be shown how such architectures could look like and how and why CANFD is one of the key technologies meeting future requirements.

The benefit of CAN FD for future vehicle architectures

At the time when CANFD was introduced by BOSCH in 2012 [1] researchers have already been working on the next big thing for in-vehicle networking: automotive Ether-net [2]. Virtually the introduction of automotive Ethernet pushed the introduction of CAN FD as a consequence. The future requirements have mainly two effects on the vehicle's E/E architecture: growing complexity and the demand for much higher bandwidth in some parts of the network. This can be handled best by means of structuring the architecture into different domains (e.g. body, chassis - ADAS, powertrain and telematics). Figure 2 shows an exemplary automotive E/E architecture structured into four domains interconnected by an Ethernet backbone network. Theoretically this backbone structure could also be realized using another bus system, however only Ethernet can cope with the amount of data that is currently being anticipated for future use cases.

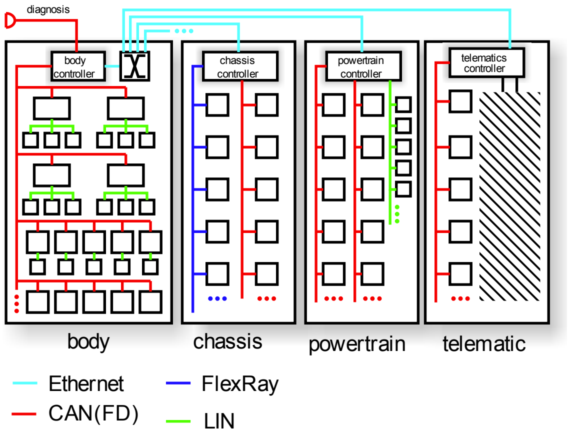

Figure 2: multi domain architecture with Ethernet backbone structure [8].

Apart from the backbone Ethernet structure there are also requirements inside the domains themselves that imply the usage of further Ethernet sub-networks inside the domains, as indicated in figure 2 e.g. inside the telematics domain.

This intensive usage of automotive Ethernet brings about the necessity to introduce new communication concepts [2]. Automotive networking by now mainly requires sensor actuator busses where small messages are exchanged with low latency and high cycle repetition time. The protocol overhead in systems like classical CAN, LIN or FlexRay is designed to be low and the maximum PDU size (protocol data unit) is typically limited to 8 byte. (FlexRay might be using up to 254 byte per frame, however it is used in practice with much smaller frames due to its predefined cyclic operation manner.) Ethernet however was originally developed for completely different applications – local and wide area networks with focus on transferring large data packets. Typical Ethernet related communication principles like switching of data packets, virtual LANs, TCP, IP etc. have been established for this purpose. Sensor and actuator systems have not been on the scope of Ethernet in the beginning. However as Ethernet is a structured system according to the ISO/OSI model it could be enabled for automotive use cases by adopted hardware (100BASE-T1) and extended communication concepts like SOME/IP (scalable service-oriented middleware over IP), DoIP (diagnosis over IP) while existing concepts like IEEE 1722 (AVB) and IEEE 1588 (precision time protocol) have been extended.

These concepts are included in the AUTOSAR software standard [3] which is the basis for all current vehicle ECUs. Another communication concept which was introduced with Ethernet into AUTOSAR is IPDU multiplexing [4]. The purpose of this feature is to cluster multiple PDUs (these might be coming from different applications) dynamically into one Ethernet frame and to wrap these into a header structure indicating identifier and size of the PDUs. The Ethernet frame itself which has a very large payload field in comparison to classical CAN or FlexRay messages can be regarded as a transport container. Only this additional step makes Ethernet efficient and flexible for automotive use cases maintaining an efficient header to payload ratio.

Apart from this, the future trends described in the introduction of this paper bring about requirements to secure communication in terms of safety and authentication e.g. for functional safety of ADAS systems or to prevent remote attacks on vehicles. These requirements are also addressed by dedicated additional communication concepts in AUTOSAR. The most important of these are SecOC [5] (secure on-board communication) which provides mechanisms to protect authenticity and integrity of data) and E2E [6] (end to end protection – different profiles exist) to protect safety critical communication in terms of fault of the communication channel, e.g. bit errors. All these mechanisms imply a considerable protocol overhead (headers, CRCs, signatures etc.) compared to the data that has to be transferred.

Automotive Ethernet can cope with these requirements as it offers plenty of bandwidth and nearly unlimited payload per message (up to 1500 byte) in comparison to the typical 8 byte payload of systems like LIN or classical CAN. Hence at the first glance automotive Ethernet seemed to divide in-vehicle networking technology into two worlds: a new Ethernet based part with plenty of bandwidth and payload per message featuring modern communication concepts and an old world consisting of classical CAN and LIN stuck at 8 byte per message, comparably low communication speed and very limited possibilities in terms of modern communication concepts.

This separation was overcome with the introduction of the new CAN FD protocol [7,8]. An increase of the data transfer by a factor of up to four and especially an increase of the payload length by a factor of 8 enabled CAN technology to keep up with the new communication concepts while maintaining its main advantages: CAN FD is like classical CAN a flexible bus that is easy to handle at a decent price ratio dedicated for a large scope of applications. A selection of the new communication concepts (especially IPDU multiplexing, see figure 3, SecOC and E2E protection) developed for Ethernet will also be adopted to CAN FD which is only sensible due to the availability of an extended payload of 64 byte. Hence many CAN nodes can be switched over to the world of new communication concepts but anyhow continue using CAN technology.

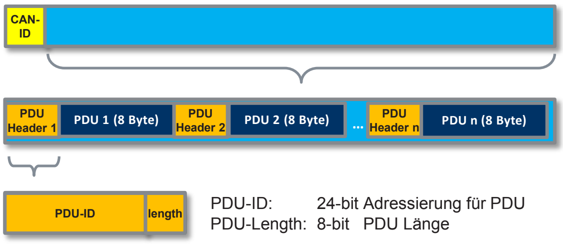

Figure 3: IPDU multiplexing for CAN FD

Practical application of CAN FD

While developing the next generation of the vehicle E/E architecture many classical CAN networks will be migrated completely to CAN FD. However approximately half of the CAN FD networks that will be introduced are due to new applications that did not exist in previous architectures. This means that CAN FD is not just a replacement for existing classical CAN networks it also directly captures new applications. Even though there will be automotive Ethernet with several nodes in the next generation of the vehicle E/E architecture a growth of CAN interfaces can be observed as well which indicates that CAN is still a growing technology [9]. This growth however is mainly observed for CAN FD components.

With regard to the distribution of CAN FD over the different domains it can be stated, that there's no typical domain or use case for CAN FD which approves that CAN FD is a very universal system like classical CAN is today. Actually CAN FD can be found in any domain of the next vehicle E/E architecture generation. The same is true with respect to communication speed. It will be used in large networks with many nodes at comparably low communication speed (e.g. 250 kbps/500 kbps) as well as in small networks with few nodes and high communication speed (e.g. 500 kbps/ 2 Mbps). And for some applications a value in-between is optimum (e.g. 500 kbps / 1 Mbps). This scaling of different communication speeds however is mainly due to the physical limitations of the CAN FD physical layer.

From the network designer's point of view one single communication speed would have been preferable but this trade-off is necessary to match the different requirements with the given CAN FD physical layer. It has been shown [10] that e.g. a communication speed of 500 kbps/ 2 Mbps is only possible in limited physical topologies.

Finally it has to be mentioned, that classical CAN has not yet died out. It will still be part of future vehicle E/E architectures, especially for carry-over components and use cases that do not yet require new communication concepts introduced with automotive

Ethernet technology. However a decline of classical CAN in favour of CANFD is obvious. In the long run it can be anticipated that there will only be CANFD components left besides some historic remains (e.g. diagnostic CAN).

Implications of CAN FD – from the everyday business of an OEM

Size of topologies – In the beginning there were high expectations about the achievable data rate of CAN FD. BOSCH was showing a demonstration with 10 Mbit/s and more [11]. So in the beginning even 8 Mbit/s have been under discussion for standardization. The assumption was, that the arbitration process would be the main limiting factor for CAN communication speed in general. But after intensive investigations on failure mechanisms it soon became clear the asymmetric distortion of the CAN signal on the physical layer is the limiting factor of CAN FD networks in the data phase [10]. The definition of the transceivers' maximum allowable asymmetry by ISO11898-2:2016 and the research by BOSCH about the maximum allowable asymmetry of received signals in CAN FD networks ("phase margin") are today the basis to assess CAN networks [12]. In an intensive analysis about the phase margin characteristics of different topologies it became clear, that with today's CAN physical layer the freedom in topology creation is very limited if the network should work at 2 Mbit/s in the data phase [10]. Even though 5 Mbit/s have been defined by ISO this speed is currently not feasible under automotive conditions. Referring to this a further improvement of the CAN physical layer (especially for transceivers specified at 5 Mbit/s) would be desirable.

CAN cables – During the investigations to optimize the CAN FD topologies [10] it also turned out, that the cable characteristics become more and more important with rising communication speed. In the past little attention was spent on the electric characteristics of CAN cables. These had to meet the thermal and mechanical requirements and apart from that primarily they had to be cheap, whereas electrical characteristics have not been specified in the past. When using arbitrary CAN cables it was found that even optimal line topologies which are typically free from any reflections yielded a substantial amount of asymmetry. The reason for this was found out when analysing the topology shown in figure 4.

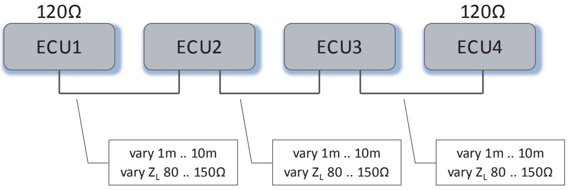

Figure 4: Line topology for 2 Mbit/s CANFD

The analysis result given in figure 5 shows a Monte Carlo method analysis of this topology with varying characteristic line impedance and line length as given in figure 4.

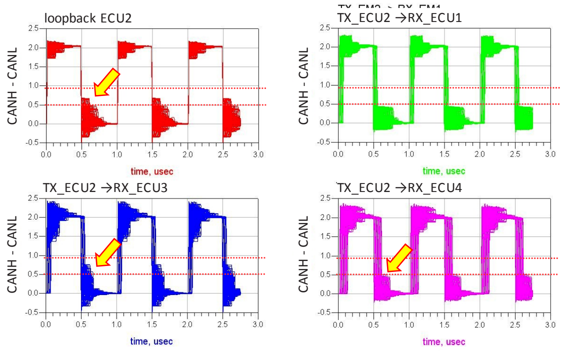

Figure 5: Montecarlo analysis of line topology @ 2 Mbit/s

This simulation result neglects the frequency dependent attenuation intentionally in order to point out the effect more clearly. There are substantial reflections at the 120 Ohm terminations on both sides of the bus as line impedance and termination do not match, which results in signal distortion at the edges of the CAN signal. Especially the dominant to recessive edge is affected as the signal distortion exceeds the switching threshold of the CAN receiver at 500/900 mV; see dashed lines in figure 5. The effects at the recessive to dominant edge however happen on a higher voltage level not touching the switching thresholds – the result is asymmetry. If the transmission line characteristic impedance is fixed to 120 Ohm the reflections will be removed completely, as can be expected.

There are different possibilities to solve this issue. The first is to control the cable characteristic and force the cable to have 120 Ohm. However this implies that the thickness of the insulation material has to be increased. Especially for the widely used cable type FLRY-A with 0,35 mm² cross section this means that these do not fit to standard automotive connectors anymore, especially those connectors that are sealed in the engine compartment and the outside of the vehicle are affected. The second possibility would be to lower the CAN termination in the end nodes to 100 Ohm which is quite close to typical FLRY-A-2x0,35 mm² cables. New CAN transceivers according to ISO11898-2:2016 are able to optionally drive up to 45 Ohm load. However in the end all possible solutions to this issue require some trade-offs.

Wake up function – The possibility to wake up CAN nodes over the network has been introduced a long time ago (ISO11898-5) and this technology is widely used today. However when using the CAN FD protocol in the network some of the assumptions made for ISO11898-5 are not valid anymore. In a CAN FD message with 500/2000 kbps it is not ensured that there is a dominant phase of at least 5 μs as a transceiver according to ISO11898-5 requires to wake up (cf. "CAN activity filter time"). In the classical CAN protocol this was always ensured by the consecutive RTR, IDE, FDF bits for 11-bit ID frames and the RTR, FDF, r0 bits for 29-bit ID frames. For CAN FD frames this is not the case, as can be seen from table 1. For CAN FD frames with 29-bit IDs there are constellations even without any two dominant consecutive bits in the control field.

Table 1: worst case CAN and CAN FD wake up timing values

frame	consecutive dom. bits	dom. @ 500 kbit/s
classical frame 11-bit ID	RTR IDE FDF	6 μs
classical frame 29-bit ID	RTR FDF r0	6 μs
FD frame even ID, 11-bit ID	ID18 RRS IDE	6 μs
FD frame odd ID, 11-bit ID	RRS IDE	4 μs
FD frame even ID, 29-bit ID	ID0 RRS	4 μs
FD frame odd ID, 29-bit ID	n/a	2 μs

In ISO11898-2:2016 this issue was addressed by adding an optional "CAN activity filter time" of 1,8 μs, i.e. a dominant phase of 1,8 μs would be enough to wake the bus. This will ensure safe wake up with any CAN or CAN FD frame using 500 kbit/s arbitration speed or less and any speed in the data phase. Since transceivers supporting this feature have not yet penetrated the market special measures have to be taken by the OEM to ensure safe wakeup. There are several possibilities:

1. Generally limit the ID range in order to ensure that there's always three consecutive dominant bits in any ID used.
2. Use classical CAN messages for bus wake-up.
3. Use dedicated CAN FD messages for bus wake-up with at least three consecutive dominant bits in the ID field.
4. Use dedicated CAN FD messages for bus wake-up with at least three consecutive dominant bits in the data field. Transmit these frames with arbitration speed in the data phase, i.e. BRS = dominant.

Some more options may exist. All of them implicate trade-offs. The first solution is easy to implement but it restricts the usable ID range a lot. All other solutions require a special priority treatment of the wake-up message in the ECUs' software stack. It has to be ensured that this is really the first message which is put into the transmit buffer of the CAN controller in an ECU that intends to wake-up the bus. If this is not ensured another message might be sent first and the network will get stuck without waking up.

Expectations for CAN FD in future

It has been shown that the introduction of CAN FD was the right innovation at the right time. CAN FD perfectly complements the newly introduced Ethernet core networking structure of future vehicle architectures. The increased communication speed but especially the increased payload field enable CAN FD technology to keep up with future communication mechanisms and networking concepts that came along with automotive Ethernet technology.

During the development process several shortcomings of CAN FD were detected which mainly affect the physical layer. Some of these have already been addressed by

ISO11898-2:2016 and it's only a question of market penetration to solve these (e.g. wake-up). Others still require the further improvement of the CAN physical layer.

The final goal should be to achieve 5Mbit/s in the data phase over networks that are comparable in terms of flexibility and dimensioning to classical 500 kbit/s CAN networks. This could be achieved by means of technologies that especially improve the signal integrity of the dominant to recessive edge. One approach could be the so called "ringing suppression technology" as proposed in CiA601-4 [13].

CANFD with communication speed above 5 Mbit/s is doubtful. On the one hand there's currently no physical layer available for this, on the other hand the bit time settings and the required clock speed become more and more inappropriate with increasing communication speed. Eventually 10 BASE-T1 Ethernet, a cheap extension to 100 BASE-T1, is expected to put a natural limit to CANFD expansion for higher speed.

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