From FlexRay to CAN-XL: Migrating real-time high-performance networks into the future

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FlexRay was designed to provide a high performance networking technology to cope with time critical communication demands in drive- and powertrain control loops between ECUs distributed throughout the car. Due to its complexity, limitations and involved costs, it only found its use in premium cars and chip supplier as well as OEM market acceptance was not the best.

The VW group has started to consolidate its EE architectures towards E³2.0 for all types of cars, e.g. volume, premium, sports etc. and a solution was required to have one technology for all, together with some other handy features and thus, supported the development of the next generation CAN networking technology, named CAN-XL.

This article/presentation will show the challenges and gained possibilities of migrating FlexRay networks to CAN-XL using the example of the powertrain, also considering CAN-FD and why it is only an intermediate solution.

1. From FlexRay ..

FlexRay [1] started to allow time triggered fast network communication for use cases like x-by wire in a world of in vehicle networking, where CAN was „high speed".
Those use cases required redundancy by concept, a synchronised system by design to allow precise causal computation and control loops in the power- and drivetrain as well as the first steps for assisted driving.
In order to be such a save and reliable system, it required a fully fledged specification, where almost no room for inter-pretation was given. Plus, it wanted to be as flexible as customers wanted it to be used when it comes to communication schedule design, redundancy, topology complexity by active star couplers, etc., adding even more configuration parameters.

This vast amount of configuration parameters and cross dependencies, making it serioulsly complex and expensive to handle.
Further, the physical layer was a challenge and had to be limited due to some design constraints, such as the majority voting and configurable receiver thresholds leaving almost no room for flexible networks under generalised configuration setups.
Together with having expensive semiconductors it led to expensive and node number limited daisy chain like networks, although more seemed to be possible in a lab.

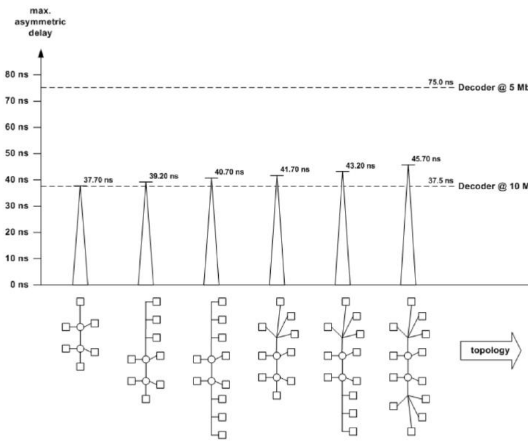

Figure 1: Asymmetric delay limitations at several topologies (Source: ISO 17458-4)

Not to mention the additional, layer 1 switch like active star couplers, dealing with the distribution of nodes over daisy chain and node number limited branches.

The daisy chain topology type was therefore a consequence of the network configuration and system robustness demands, although star based topologies were not forbidden. They suffered at their implied asymmetric delays, leaving no room for robustness against external influences, please also see figure 1 above.

Daisy chains further added more required PCB space, connector pins and more design rules on signal traces at ECUs, as iCC 2024 connector concepts for daisy chaining were too expensive in comparison.
Finally, the daisy chaining of networks brought limitations in flexibility in production when it came to flashing and calibrating of ECUs, if not all ECUs were assembled to the vehicle at the same time and simple parameters such as bus terminations could not be met.

The communication demand to use FlexRay increased a lot over the previous vehicle generations, starting with only a handful of ECUs and distinct daisy chain topologies up to more than 20 ECUs with more than 10 distinct daisy chain topologies, please see figures 2 and 3 below.

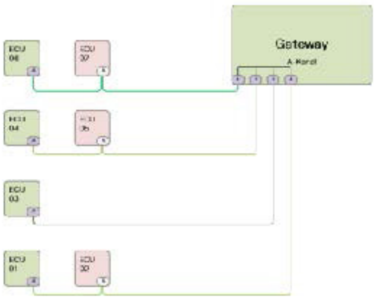

Figure 2: first generation FlexRay vehicle

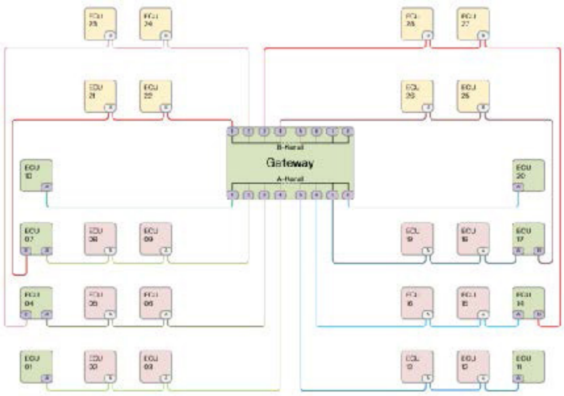

Figure 3: third generation FlexRay vehicle

This implied, that communication schedules got more crowded, limiting the available communication slots for each ECU and configuration / calibration at production line got more complex to handle.

To keep up a good and robust synchronisation, time slots on the other end had to be limited / covered against each other with a lot of configuration "pillows", leaving only a small amount of a possible net data rate and consecutively limited number of ECUs in a FlexRay channel, other than what would be possible in theory.

The idea of having different lower speed grades on top of classic CAN to relax the daisy chain limitation could not overcome the complex protocol configuration and the acceptance was still low.

Challenges:

- Overall system cost (semiconductors, wiring harness)
- Overall development cost (configuration complexity)
- Physical layer system design limitations (daisy chain)
- Production line limitations (configuration, calibration, flashing)

Because of the above challenges and implied costs, which is not able to be handled in volume cars and the market pressure on costs, this low market size leads to a phasing out of this technology in new architectures and new ideas are required to now fill the gap between multiple node classical networks like CAN [2] and way faster, but even more expensive point to point technologies on the other end and enabling re-usability / sharing of hardware and software between premium and volume architectures.

2. .. via CAN-FD ..

One, but probably the only one left possible option in terms of cost and system design flexibility in the mid 2010's was using newer CAN-FD [2] technology for faster data rates and bigger payloads than classic CAN, to still provide assisted driving and faster causal computation and control loops in a reasonable way for volume cars.
CAN-FD offers bigger payloads over classic CAN (64 bytes over 8 bytes), but still not as much as FlexRay provided (64 bytes over 256 bytes).
The fear of excessive ringing at data rates higher than 500 kBit/s through its CSMA/CA scheme with only one actively driven dominant level led to excessive amounts of analyses to cope with the wanted and needed network flexibility as similar as classical CAN offered.

Signal edges have become faster than before, adding a way bigger di/dt, challenging the system behaviour determined by the passive components and parasitics in the respective parts when switching from dominant to recessive signal level.

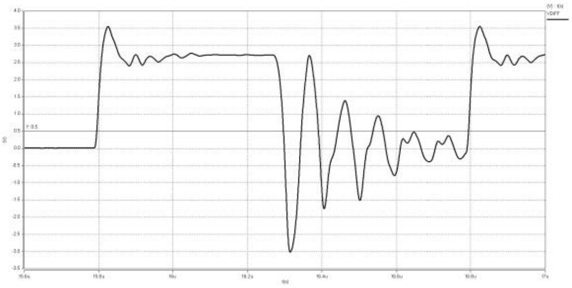

Figure 4: Example of ringing in a CAN-FD network

Prior to the introduction of CAN-FD in VW group cars (volume and premium) in 2019, many investigations have been conducted to check the system behaviour for networks running in different configurations between 500 kBit/s and the desired and reasonable data rate of 5 MBit/s.

It turned out, that networks in (multiple)star configuration for the most flexible use with 5 MBit/s were extremely sensible and prone to ringing in areas where a system designer doesnt want them to be.

It also turned out, that reducing network flexibility down to daisy chains adds other types of issues (e.g. plateaus in the area of receiver thresholds), please see figure 5 below showing the TXD and VDIFF signal of a high ohmic ECU inside the daisy chain at a desired network topology size about to turn over 0.5 V threshold.

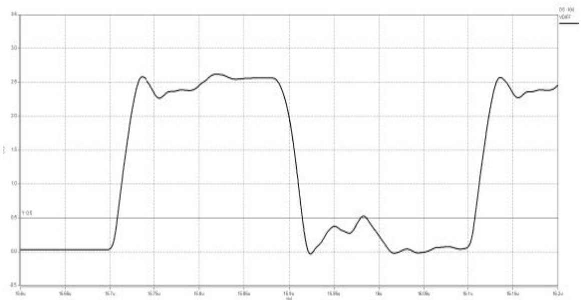

Figure 5: Example of CAN-FD daisy chain based signal plateau

The total line length and number of nodes had to be stripped down to a very short end, which led to a refusal using 5 MBit/s in our systems.

Thus, judging by the signal quality in those systems, being no alternative fallback or future proof solution.

From physical layer based behaviour, systems were more on the edge than before to reach the increased use case complexity with e.g. assisted driving and playing the symphony of the affected sensing, computing and actuating parts throughout the car, not to mention increased comfort and infotainment demands.

Flexibility in network topology size in terms of number of nodes and total line lengths was less compared to classical CAN, but still better than FlexRay, as production line limitations could be omitted by star based network topology layouts as well as customer demand based assembly of ECUs in such network topologies, please see figures below.

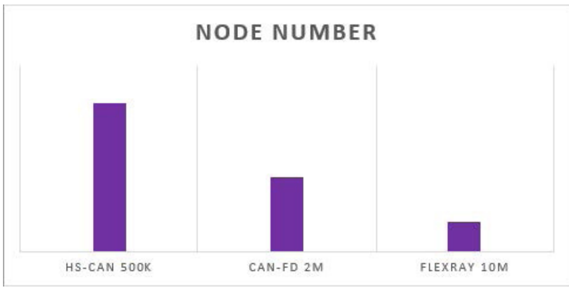

Figure 6: Node number comparison between HS-CAN, CAN-FD and FlexRay with maximum data rates, based on single wire harness topology layout limits

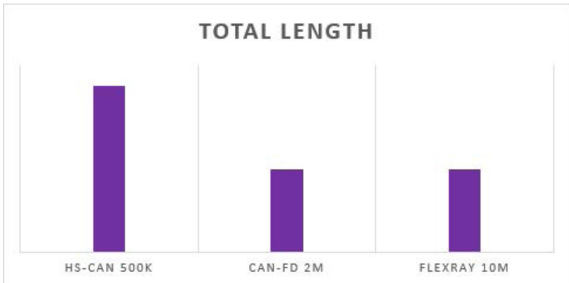

Figure 7: Total length comparison between HS-CAN, CAN-FD and FlexRay with maximum data rates, based on single wire harness topology layout limits

Additional to the physical layer aspects, by the nature of the CSMA/CA bus access method in CAN-FD systems, to reach as less latencies and respective timing jitter, busloads had to be kept unusually low to reach realtime behaviour. Such bus loads were required to be the half of bus loads from other "regular" networks together with short payloads and limited number of messages.

This effectively limited the net data rate, compared to what is possible with FlexRay by guaranteed bus access within a given communication cycle time.

Challenges:
- Physical layer system design limitations (very sensible network topology layouting for every ECU combination)
- Overall system cost (multiplication of number of networks to cover customer functions coming from FlexRay: bigger microcontrollers, increased PCB size, increased wiring harness)
- Balancing act between limitation of functionality and multiplication of number of networks

The challenges above show, that more networks were needed to overcome physical layer and protocol layer limits.

As a side effect, microcontrollers and necessary PCB space for central ECUs became bigger and more complex just by requiring more interfaces and computation for routing and synchronising data.

Using CAN-FD for realtime requiring customer functions can now be built up for either volume or premium cars on the same technology basis, but requires complex scaling of central computing domains to manage customer functions in conjunction with market pressure on costs.

Therefore CAN-FD can only be an intermediate step substituting FlexRay.

3. .. and CAN-SIC ..

Handling the fears of “classical” CAN switching behaviour, which limits network sizes and flexibility, CAN-SIC [3] was invented. It still allows a dominant over a recessive signal level on the bus. But in contrast, actively consuming the energy driven from dominant states in the network system.

This further era brought back flexible networks sizes almost like former classical CAN systems, but now e.g. 4 times faster on one hand, or speeding up the data rate to 5 MBit/s for robust designs in harsh environments, allthough single devices might be able to do 8 MBit/s in special environments or labs, please see figures below.

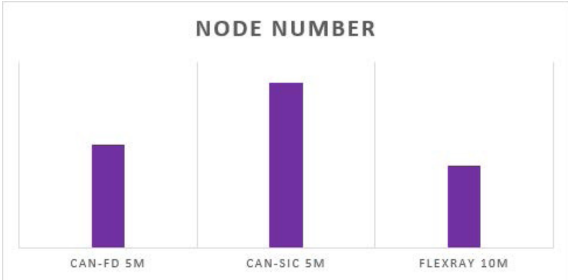

Figure 8: Node number comparison between CAN-FD 5 Mbit/s, CAN-SIC 5 Mbit/s and FlexRay 10 Mbit/s, based on single wire harness topology layout limits

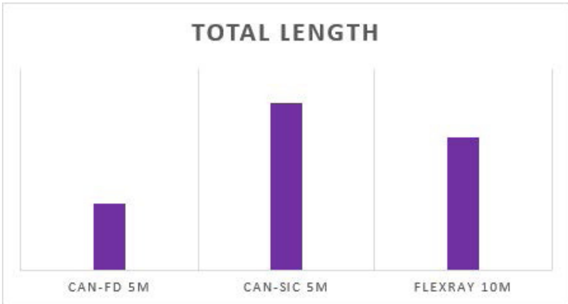

Figure 9: total length comparison between CAN-FD 5 Mbit/s, CAN-SIC 5 Mbit/s and FlexRay 10 Mbit/s, based on single wire harness topology layout limits

With CAN-SIC, a solution is coming near by having something, which is also an option for cost sensitive volume cars. But it has two „but’s“.
First, there is still the limitation of the protocol layer, needing almost “empty” communication schedules for realtime communication of the causal computation loops required in the power- and drivetrain together with still limited number of payload bytes for the contrary use case on the same bus, e.g. for flashing.
Second is, that even though the physical layer has heavily improved, the first switching edge before transmitter based signal improvement circuits are becoming effective is still travelling among the network topology.
It is just adding a serious glitch which could reach receiver thresholds around sampling points, please see example figure below.

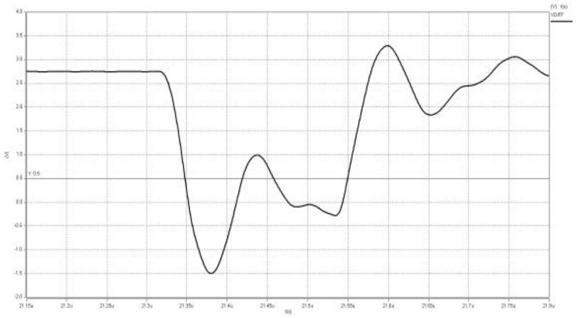

Figure 10: Example of CAN-SIC based signal glitch in a star based topology (5 Mbit/s, 6 nodes, 30m)

This is limiting the network size again too early compared to the maximum possible distance between two nodes with still working arbitration and signal improvement at given arbitration and data rates of up to 5 MBit/s, please see figures 8 and 9 again.

Huge amounts of analyses had shown, that using flexible star based networks could increase this glitch to an even more serious amount, especially for systems running at 5 MBit/s data rate.
That unfortunatelly led to falling back to daisy chain like systems with its inflictions of drawbacks in more PCB space, connector pins, longer total line length compared to star topology scheme, handling wiring harness optimisation as well as limitations in configuration, flashing and calibration at production line.
Star based networks at a data rate of 5 MBit/s had to be limited too strictly to small local zones, leaving no room for realtime applications throughout a car, much similar to CAN-FD at 5 MBit/s.

Nowadays, more demands on functional safety and intrusion / manipulation pre-vention come into play. Coping with the protocol limitations and increased amount of data thus to be transferred due to

- more sensor/actor data and faster synchronisation / update cycles and
- additional safeguarding of communicated data,

this adds even more sibling networks to the car – a challenge, FlexRay had not to deal with at that time. One could imagine, that even more FlexRay networks and bigger active stars would've been necessary.

Using CAN-SIC would still ease the protocol and above layer implementation compared to FlexRay, but again eats up BOM cost reductions just because of having bigger microcontrollers with more interfaces to be handled as well has having a multiple of hardware interfaces represen-tations in an ECU.

Challenges (for 5 Mbit/s systems):

- Physical layer system design limitations (very sensible network topology layouting for every ECU combination)
- Overall system cost (multiplication of number of networks to cover customer functions coming from FlexRay: bigger microcontrollers, increased PCB size, increased wiring harness)
- Production line limitations (configu-ration, calibration, flashing)

So, CAN-SIC cannot be the final solution. It requires workarounds with costy pre-misses, such as more interfaces, bigger microcontrollers, bigger connectors, more wiring.
High level automatted driving requires even further communication margins, currently designed systems arent able to provide yet
.

4. .. adding zonal architectures to the equation ..

Zones can break up huge domain based networks and reduce wiring harness complexity, but routing is nowhere in the near of being designed for fast and realtime communication throughout a car, although bandwidth “seems” to be “unlimited” in the backbones.
This bandwidth comes with a cost in terms of expensive switches, long start-up times, massively increased amounts of interrupt loads and again increasing microcontroller sizes.
Precision time protocols might help, but this is kind of a „delayed“ or „timed“ realtime and information must be available, where it is needed in time and not “lost” through several zonal routings, competing with other routed data.
This would make computation loops more complex, if anyhow possible, to overcome these delay sources and more „guessing“ of what really happens at a certain point in time with the vehicle moving.

With zone based network architectures, a central computing or zone collecting instance grows bigger and bigger to handle this sheer amount of interfaces, please see example figure below.

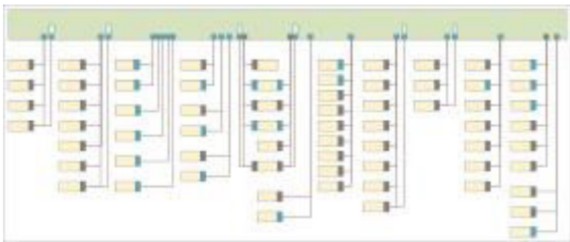

Figure 11: Example of number of CAN based interfaces on a central computing or zonal ECU

Challenges:
- Physical layer system design limitations (either CAN-SIC daisy chains or complex Ethernet based systems)
- Overall system cost (multiplication of number of networks, expensive backbone routing)
- Delays due to several zonal routings strongly decrease realtime capability

Realtime critical causal computation loops controlling the moving state of a vehicle, with current available technology, still require a domain and respectively signal based bus throughout the vehicle, where again the physical layer limitations of a fast CAN-SIC network at 5 Mbit/s kick back in with more domain based sibling networks throughout the vehicle than probably necessary.

5. .. to CAN-XL.

The previous sections have shown the challenges and limitations of existing technologies and latest architecture designs to overcome. Summing them up, the following expectations shall be met by the new technology:
- realtime communication capability
- reasonable amount of nodes in a network topology
- reasonable flexibility and size of network topology layouting, also meaning no daisy chain necessity by strong physical layer design
- reasonable amount of payload per message
- overall development cost reduction due to less sensible physical layer specification design and less system configuration complexity
- overall system cost reduction via reduction of interfaces in domain / zonal / central computing as well as complex sensor/ actor ECUs by reduction of sibling networks due to technology limitation workarounds
- breaking up of classical CAN / CAN-FD communication matrix design for even better performance and bandwidth margins
- scalability of network technology for use without limitations in customer functionality
- breaking up of production line limi-tations in terms of configuration, calibration, flashing)

CAN-XL [4][5] comes with
- way faster data rates compared to CAN-SIC, way bigger payloads (2048 bytes over 64 bytes),
- more defined support on higher layers, e.g. for savety and security manners,
- the capability of being attached under Ethernet based higher layers and most importantly
- a physical layer to overcome behavioural limitations of FlexRay, CAN-FD, CAN-SIC and other competing network technologies at comparable gross data rates.

How this can be proofed, is shown in the next sections.

6. Analysis preface

A practical example shall show, how a network system migration towards CAN-XL can be done. This takes an already transferred communication system example from FlexRay to CAN-SIC, as the focus shall not be the transferral from synchronous time triggered to asynchro-nous arbitration based communication scheme, but the consolidation of already designed CAN-FD / CAN-SIC networks.
Sharpening the focus, two example CAN-SIC networks are taken into account, which could represent the split of a realtime and additional data communication for a system design within a possible power- or drive-train.

The goal shall be a realtime communication having these two network topologies consolidated back on one bus, which required to be split up from a FlexRay system design.
This consolidated bus shall take both communication setups into account and furthermore shall be designed to work from physical layer perspective under all environmental conditions and specification limits.
For this, two different analyses are done. The first covers the consolidation of the communication on protocol layer by calculations (section 7) and the second covers the feasibility of the physical layer by simulations (section 8).

Protocol layer

One of these sibling networks sends realtime data for fast control loop precision. The other bus takes all the „organisational“ and „safety/ security“ related overhead.

Within this context several meanings and system measures will be used:

- **realtime:** shall be a communication loop in the area of less than 5 ms, where data shall be available between a given sender – receiver combination in a repetitive manner.
- **message cycle:** repetitive trans-mission loop of a message.
- **cycle jitter:** timing variation of the message cycle based on best and worst case prioritised bus access.
- **latency:** time for the transmission of a message from message buffer at a sending node over the network topology to the message buffer of a receiving node
- **minimum latency:** latency value for the transmission of a message with immediate and undisturbed bus access
- **worst case latency:** latency value for the transmission of a message with worst case bus disturbance
- **bus load:** average time of active message transmission / communi-cation time over a given time period

All of the above described system measures are affected by the configuration of the active communication time on the bus and its detailed configuration, which shall be kept as low as reasonable and equally distributed.

Equal distribution at first is affected by the differing size of message payloads and number of messages in conjunction.
Equal distribution further requires a proper scheduling of message cycle loops in a communication setup for a bus system inside the participating microcontrollers in the ECUs, meaning not all message cycles start at a defined cycle start point in time. How to achieve this, will not be discussed in this document.

Bus load is affected by the number of messages sent on the bus, as well as by the length of data to be transmitted in each message and the used cycle time for each message.
In CAN systems up to CAN-FD protocol, the arbitration length via the use of standard or extended IDs is also affecting the bus load. At CAN-XL protocol use, only standard IDs as so-called priority IDs with a fixed length are used [4].
Less messages for less arbitration over-head, lower message cycles and less message payload data basically lead to lower bus loads.

The latency is affected by the number of messages sent on the bus and especially the length of data in each message, together with its priority identifier and message cycle.
Less messages for less arbitration over-head and losses as well as smaller message payloads basically lead to lower latencies, respectively lower minimum and worst case latencies.
Worst case latencies together with message cycle times directly affect the cycle jitter.

Message payloads at CAN-FD protocol are additionally affected by the limited and not byte wise configuration of the DLC.
Payloads above 8 bytes almost always added fill bytes to conform the DLC configuration in case of signal data being not a multiple of 4 (up to 24 bytes) or 8 (up to 32 bytes) or 16 (up to 64 bytes). This limitation is no longer existing in CAN-XL and byte-wise configuration is possible.
The derivation of the formulas behind the calculation of the latencies, bus load and cycle jitter are based on an internal paper [6].

Physical layer

For the physical layer analysis, a reference model for mixed signal (analogue, digital) simulation was developed, which can be configured in different manners to walk on the physical layer specification limits, given in [5]. These include for example output driver slopes and amplitudes, as well as transmitter and receiver asymmetries.

Further MDI and transmission line components were taken from existing simulation eco systems for CAN-SIC and FlexRay.

System termination values have to be derived based on the number of expected ECUs and total line length in one network topology to stay within physical layer specification limits. This is not being discussed in this document.

Within the physical layer context, several meanings and system measures will be used:
- **signal integrity:** describes the necessary level of signal quality at the CAN bus pins analysed by appropriate qualification criteria
- **eye diagram:** single bit wise qualification criterium on the convoluted differential signal between CAN bus pins

The signal integrity is evaluated by the measurement of the eye diagram at each sender – receiver combination in the network topology at each receiver, except the sender itself.
The eye diagram is configured by means of the possible asymmetries, passive parasitic effects (based on the expected network topology size in terms of number of ECUs and total line length) and tolerances in the system, safety margins for EMC robustness and bittiming configuration.
The maximum eye opening is at the sampling point, which is configured to be in the middle of the bit plus one time quanta.
The calculation of the values mentioned above is not part of this document.
Many analyses via simulation testbenches, lab and EMC chamber measurements have shown, that the switching between slow and fast mode at CAN-XL turns out to be less as critical as the pure signal integrity at the fast mode.

However, the switching from slow to fast mode has still an impact on the asymmetry on the first fast mode bit pulse on the bus, a reasonable PCS layer stimulus implementation is necessary for simulation based analysis.

7. Communication Setup Analysis

FlexRay as a time synchronous bus system has regularly a reasonable message cycle of 10 or less milliseconds with theoretically no cycle jitter, meaning the worst case latency basically being equal to the minimum latency.

By the arbitration scheme used in CAN based asynchronous bus systems with prioritized bus access, cycle jitter is very likely to happen and worst case latency itself as well as cycle jitter must be limited, even when keeping fast message cycles equal to or less than the realtime window.

The premise for a possible consolidation shall be to keep the quality of the realtime communication besides the additional communication demand in one single CAN-XL network from the former sibling networks in terms of the initial bus facts.

Furthermore, there shall be room for future extensions of the target CAN-XL bus, if further functionalities or ECUs are added to the network.

The following figure 12 shows the initial facts from the two busses, running at CAN-FD protocol with 0,5 Mbit/s arbitration rate and 5 Mbit/s data rate and signal based communication setup.

The calculations shown below ignore any non-cyclic messages in the communication setup, as these are defined to play no role for the computational loop operation and repetitive exchange of vehicle state data during customer use. Examples would be developer, diagnosis, flashing or similar messages.

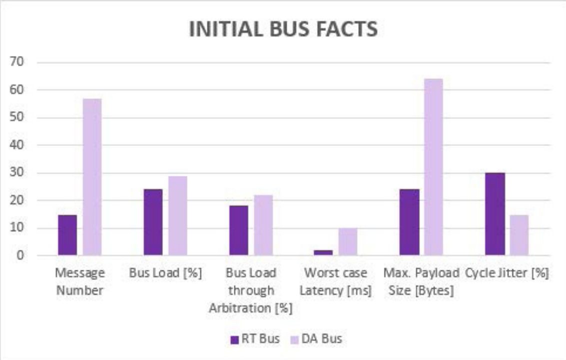

Figure 12: Initial bus facts of the realtime bus (RT) and data bus (DA) before merging to CAN-XL

The message amount sent to the data bus is around 4 times the value of the realtime bus. The bus loads are in the range of approx. 24 to 29 % with approx. 18 to 22 % over-head by arbitration.
The worst case latency at the realtime bus calculates to 2 ms and at the data bus to 10 ms.
The minimum used message cycle at the realtime bus is 5 ms and the maximum used message cycle 200 ms, whereas the numbers for the data bus are 10 ms and 1000 ms.
The maximum used payload at the realtime bus is 24 bytes or less and at the data bus 64 bytes or less.
The cycle jitter at the realtime bus reaches 30 % especially at messages with low message cycle time and low priority identifier due to many fast messages with very low message cycle times. In contrast, the cycle jitter at the data bus is approx. the half of the value due to no messages with very low message cycle time, blocking the transmission of other messages with lower priority.

Raw Merge

The first step to one CAN-XL bus is the raw merge of the communication setups from both intial CAN-FD busses.
With this raw merge, the arbitration rate will be kept at 0,5 Mbit/s and data rates from 10 to 20 Mbit/s are analysed.
Please see the intial comparison of the raw merger from the sum of both CAN-FD busses (light grey bars) to CAN-XL with 10 Mbit/s (light violet bars) and 20 Mbit/s (dark violet bars) in Figure 13 below.

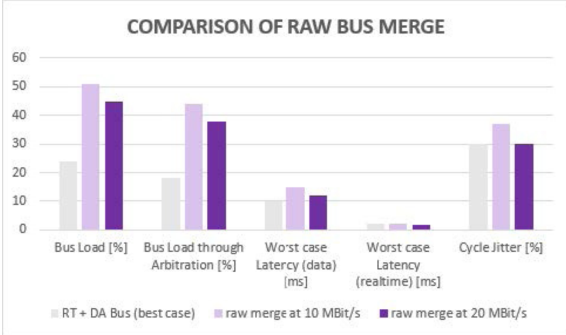

Figure 13: Comparison after initial merging to CAN-XL

This first comparison shows, that as expected, the bus load increases heavily due to the combined number of messages from both initial CAN-FD busses.

This further implies, that the bus load overhead by arbitration increases accor-dingly and the worst case latencies for the data bus related messages increase by some ms. The worst case latency for the realtime data remains around 2 ms or slightly better and the cycle jitter keeps the same dimension.

To possibly gain more potential with the CAN-XL technology, another paradigm in communication setup design shall be analysed in contrast to nowadays signal based communication with probably un-changed message routings througout a vehicle and equal cycles for application and message transfer.

Two different optimisation approaches shall exemplarily show, how this can be achiev-ed. Both initial busses operate with 6 ECUs, which plays a role at the discussed optimi-sation steps.

Optimisation

The first approach focuses on reducing the bus load by a consolidation of signal data sent by one ECU into only a few messages. This means, that at first data with nearby message priority and cycle time is merged into as less messages as possible.

As a premisse for the consolidation of signal data, only application based data will be merged. Other signal data, e.g. for network management, shall remain untouched.

To reach a bus load as low as possible, a good balance has to be found with regard to which messages are consolidated into each other to
- not send too much data too fast and
- not send too much low priority data with too high priority

This prevents too long messages with too high priority on the bus and in general an equaly distributed message size.
The following figures 14 (for 10 Mbit/s) and 15 (for 20 Mbit/s) show the comparison between the the sum of both CAN-FD busses (light grey bars) to CAN-XL as raw merger (light violet bars) and as bus load optimised setup (dark violet bars).

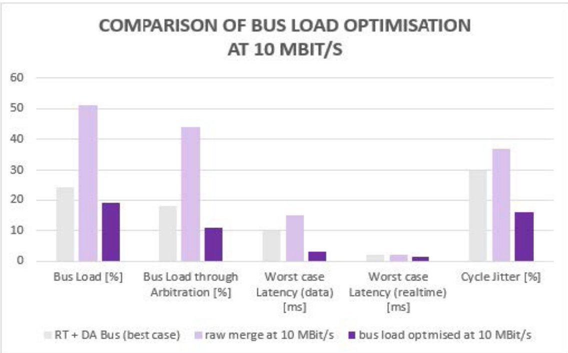

Figure 14: Comparison at 10 Mbit/s after bus load based optimisation of merged CAN-XL

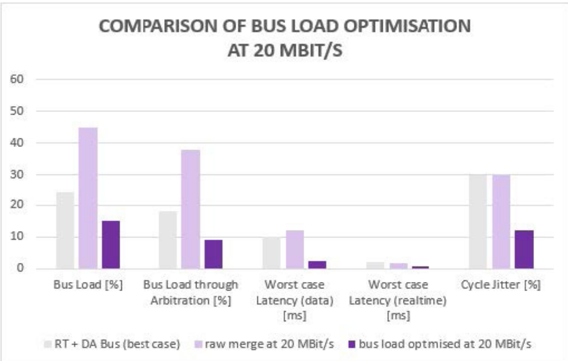

Figure 15: Comparison at 20 Mbit/s after bus load based optimisation of merged CAN-XL

The results after the bus load based optimisation show, that the achieved bus load was heavly reduced, compared to the raw merging of the CAN-FD busses and is even below the bus load of one single CAN-FD bus.

Consecutively the overal worst case latency of the data from the initial data bus improved to approx. 2.4 to 3 ms (depending on CAN-XL data rate) and for the data of the initial realtime bus to 1.4 to 0.9 ms ms (depending on CAN-XL data rate), which means that all transmitted data has realtime latency and very stable cycle jitter of even less than the half of the raw merged bus.

With the consolidation through the first approach, the maximum payload reaches approx. 180 bytes, which is almost three times the maximum of CAN-FD. The number of messages was reduced to approx. a quarter of the whole initial communication setup.

The second approach focuses on reducing the worst case latencies even more. This will be achieved by drastically reducing the number of sent application messages to one. This implies, that all application data of each ECU is sent with the fastest message cycle and highest bus priority from the original data set of the initial busses.
The results of the second approach slightly differ compared to the first approach. The overall worst case latencies could be further reduced by approx. 0.5 ms. The worst case latencies for the realtime data remained the same.
Due to the above mentioned fact, sending all data with highest priorities and fastest message cycles, the maximum payload increased to approx. 360 bytes.
The bus loads and cycle jitters remained the same at 20 MBit/s, whereas slightly increased by approx. 2 to 3 %.
This shows, that the “one message for all” approach improves best by increasing the data rate.

8. Physical Layer Signal Quality

Besides the calculation of the communication behaviour in the previous section, the network topology must work under the desired data rates and further premisses from physical layer perspective, such as wire harness topology design shall be as flexible as with “classical” CAN networks without the use of daisy chain or linear busses.

The network topologies for drive- / powertrain are by their nature mainly located in the area around the moving axles of a vehicle, far from the passenger cabin.

Scalable electric powertrains exemplarily have accellerating and decellerating components at front and rear axle, such as one or more electric motors and possibly further active differentials or torque distributors and braking system assembled. Finally they are somehow connected to a central computing instance.
The intial example topologies are built up as CAN-SIC 5 MBit/s daisy chain networks with 6 ECUs and approx. 20 m total line length each and additional 6 inline connectors due to exemplary modular part assembly, please see figure 16 below of one of the two daisy chain based network topologies.

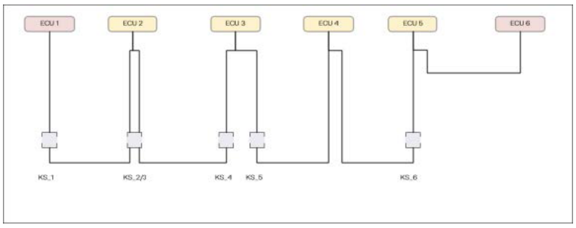

Figure 16: Example daisy chain network topology in modular setup for CAN-SIC 5 Mbit/s

Figure 17 below shows the redesign as a star based network for the most flexible combination of the given ECUs.

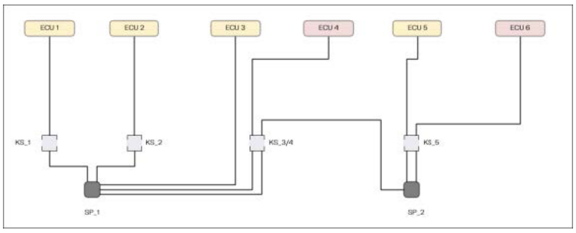

Figure 17: Example star network topology in modular setup for CAN-XL 10 - 20 Mbit/s

The yellow marked ECUs are high ohmic and the red marked ECUs are low ohmic. As this network topology system is a scalable powertrain example, low ohmic termination points must still be set at the daisy chain end points, increasing wire harness complexity, handling subsets of the full system. Star based topologies can be configured in a more flexible way keeping the low ohmic terminations stable at the minimum subset of network topology.

The remaining star based network topology design for CAN-XL is comparable to the CAN-SIC network topologies in terms of total line length and inliners, due to the exposed areas and modular assemblies of the ECUs.
In parallel to the communication setup analysis, the derived CAN-XL network topology is executed in simulation setups from 10 to 20 MBit/s and evaluated by the signal integrity measures introduced before. The creation of the eye diagram signals is done directly by a simulation model imple-mentation to provide a correct synchroni-sation of the given signals with an emulated PCS layer for worst case stimulus accor-ding to [4] as only a little overhead in the executable testbench without having a complex post processing.

The below figures 18 to 20 show the worst case signal integrity found in the network topology with worst case transmitter asymmetry and weakest transmitter output driving values and an eye opening considering 200 mV additional EMC safety margin on top of the worst case receiver thresholds given by [5].

The analyses have shown, that using the strongest transmitter output driving values does not result in worse signal shapes than already shown below.

The differential voltage signal is shown as the bold line, the synchronised eye diagram raw signals are shown as dotted line. The areas, where the raw eye diagram signals are at zero, can be ignored, because ana-logue signals must be continious.

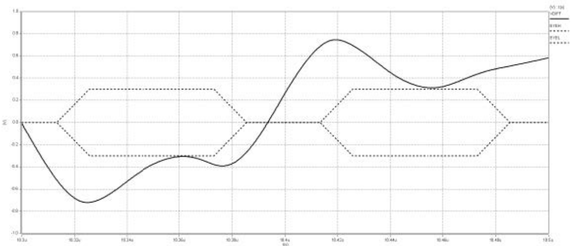

Figure 18: worst case signal integrity at CAN-XL network topology at 10 Mbit/s

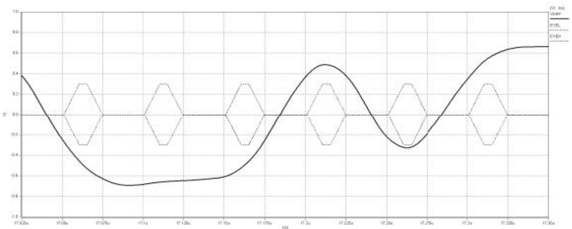

Figure 19: worst case 1 signal integrity at CAN-XL network topology at 20 Mbit/s

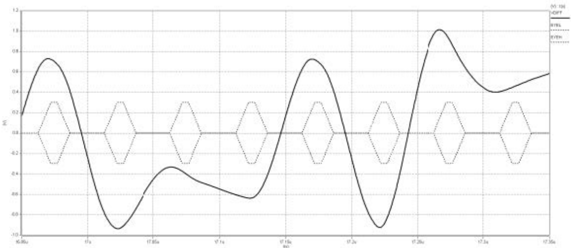

Figure 20: worst case 2 signal integrity at CAN-XL network topology at 20 Mbit/s

According to the results it can be said, that at lower data rates the signal reflections implied by the network topology layout can shrink bit amplitudes in the same bit after initiating a slope, basically stressing the sample point. Whereas at the faster bit rates the signal reflections jumping over to the following bits. This further implies, that depending on the number of sent bits of the same logical bit level have a huge impact on the signal shapes, see figures 19 and 20.
Simulations with data rates between 10 and 20 Mbit/s show the overlapping of these effects from the corner case data rates, but still keeping outside of the eye.

Together with in-vehicle EMC measurements of similar network topologies in terms of number of nodes and total line lengths, it can be said that the given example is capable of running at any data rate up to 20 Mbit/s.

9. Conclusion

Out of the communication setup analysis, the raw merging of busses, following the pure signal based communication leads to the following conclusion:

- Worst case latencies in overall are worse
- Cycle jitter can be comparable
- Bus load is worse
- Data rate only slightly improves values
- No room for future extensions
- Highest data rates are obligatory for feasible performance
- Signal based communication with nowadays applied architecture premisses is not effective when mer-ging busses

The results of the two optimisation approaches following a more flexible signal based communication leads to the following conclusion:

- Worst case latencies significantly improve to the better, although ad-ditional latencies might be considered by packing signal based data with different application cycles into less messages
- Cycle jitter significantly improves
- Bus load significantly improves
- Noticable value improvement by data rate
- Lots of room for future extensions
- Highest data rates are not always obligatory for feasible performance
- PDU based communication configuration is very effective when mer-ging busses

The results also show, that the optimisation must be done carefully, depending on the given communication setup.
Message cycles below 5 ms, e.g. 1 ms, significantly increase the sensibility to the bus load and latencies as well as increase the difference in calculated optimisation values between different data rates.
Furthermore as an example, considering faster arbitration rates could lead to almost half the values in bus loads and especially latencies when using twice as fast “classic” arbitration rates.
On the other hand, increasing the arbitration rate decreases network topology size significantly at medium to lower end bet-ween 10 to 20 Mbit/s, almost playing no role at highest data rates.
The physical layer simulations show, that any of the data rates up to 20 Mbit/s is possible, even under worst case conditions and very flexible star based network topology wire harness design.

Summing all of the previous analyses up, using CAN-XL does

- make FlexRay obsolete
- reduce the number of network interfaces in central computing or zonal ECUs
- reduce the number of network interfaces in realtime sensing/acting ECUs
- reduce the number of wiring harnesses
- omit private direct connections between realtime sensing/acting ECUs
- omit oversized automotive ethernet based and switched multiple point to point connections in realtime vehicle movement and control loops
- overally reduce development and system complexity, material use, vehicle weight and therefore costs.

All of the above mentioned benefits lead to a very lot of headroom in network design in terms of number of nodes, total line length and data rates for being a future proof technology.
The heavy improvement of flashing time through faster data rates and bigger payloads just comes as a bonus factor by the technology itself, as well as built in ethernet tunneling/routing for other than realtime based communication.
Adding functionalites can now happen with a stable and powerful physical layer, without adding more and more networks to an architecture.
This helps even more when thinking about development concepts such as software designed vehicles (SDV).

10. Outlook

Based on the analysis shown in this document, the communication setup analysis in particular, focused on the pure consolidation of signals with the noticable drawback of probably sending some data too often than necessary.
A full PDU based communication setup as a further optimisation step must be analysed. Only send data when needed and not all at once furthermore reduces the calculated bus loads and latencies giving even more headroom for a stable and future proof network design.

Finally and additionally to above, besides the stable protocol and physical layer requirements which have been manifested through analyses over the past years the following action items reside:
- Finalisation of qualification require-ments, such as CT, IOPT, IEC and CAN-XL higher layers
- Finalisation of requirement specifi-cations from semiconductor, ECU interface and wire harness perspec-tive
- Specification of PDU based communication setup design

References

[1] ISO 17458 – FlexRay Communications System
[2] ISO 11898 – CAN Communications System
[3] CiA 601-4 – CAN FD Node and System Design – Part 4: Signal improvement
[4] CiA 610-1 – CAN XL specifications and test plans – Part 1: Data link layer and physical coding sub-layer requirements
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[6] [internal] Method for analytical Latency Evaluation of time critical messages sent of CAN, CAN-FD, CAN-XL – Dr. Anna Engelmann. CARIAD SE

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