CAN FD system design challenges

Which technical concepts behind make CAN FD communication robust and how are CAN SIC (signal improvement capability) transceivers changing the possibilities for CAN FD networks?

In our previous article on CAN signal improvement, the fundamentals of the CiA 601-4 specification were reviewed, and its impact on the potential of CAN FD networks. In this article, we explore in more detail some of the technical concepts behind what makes CAN FD communication robust and how CAN SIC transceivers are changing the possibilities for CAN FD networks.

In order to define the challenges of CAN network design, one of the first points to address is how one determines what a "good" or robust network design is. When working with network architects, we start from the fundamental theory of Classical CAN and CAN FD. There is a dominant level, which is defined as a differential voltage measure above 0,9 V, and a recessive level, defined as a differential voltage below 0,5 V. This is valid irrespective of any DC common mode voltage in the background.

The signal level is measured once per bit, at the sample point. The sample point is a specific moment in time, defined as a percentage of the bit time. So, very simply: in order to make sure that a network is robust, it shall guarantee at this sample point, the signal levels shall be stable, whether dominant or recessive.

The first complication, before considering what effects can disturb the network signals, is to understand that sample points on two nodes, a sender and receiver, can and do move relative in time to one another. Therefore, if we require stable signals at the sample point, we need to calculate when the earliest and latest possible sample points may appear. We can then refine our previous statement to say that the signal levels shall be stable by the earliest possible sample point and remain stable until the latest possible sample point.

There are different factors affecting the shift of sample points:

- The drift of the oscillator in the sending and receiving nodes, where one may run fast and the other slow, creating a timing drift between the two.
- The asymmetry of the CAN transceiver, which is the difference in time between a dominant to recessive transition and a recessive to dominant transition. This is specified in the datasheet of the transceiver, with limits defined for 2 Mbit/s and 5 Mbit/s in the ISO 11898-2:2016 (for reference, refer to section 5.6 of that document). In fact, these limits are not intrinsically linked to the bit rate and many car makers now require the tighter specification of 5 Mbit/s to be met even in CAN FD networks operated at 2 Mbit/s.
- The asymmetries of the interface between the microcontroller and CAN transceiver. For calculations, both the TXD and RXD pins need to be considered, where 5 ns is a typical reference value.
- Lastly, the worst case time quanta delay. The signal may arrive at the receiver just after the last time quanta, meaning there is a worst case delay until the next time quanta measurement.

These factors are all additive and should be calculated based on a worst case bit pattern to give the longest time period between a synchronization point (a recessive to dominant transition) and a sample point, namely five dominant bits followed by one recessive bit.

These can be calculated for any bit rate, but for illustration, an example is shown for a bit rate of 2 Mbit/s with a sample point of 70 %, commonly used in CAN FD networks. Here the nominal sample point would be 500 ns x 70 % = 350 ns.

There is an additional calculation for a sending node reading back their own signal, which is also important to verify. For those who are curious, the details behind each of these calculations can be found in our iCC 2017 article "Managing the Transition to Robust CAN FD".

Table 1: Calculated asymmetries for a remote receiving node in a 2-Mbit/s CAN FD network with a sample point of 70 % (Source: NXP)

Parameter	Earliest	Latest	Note
Oscillator drift	-16,1 ns	+16,1 ns	Bit rate dependent. Assumed tolerance of ±0,3 %.
Asymmetry of sender's transceiver	-45,0 ns	+10,0 ns	Constant. Based on ISO 11898-2:2016.
Asymmetry of receiver's transceiver	-45,0 ns	+15,0 ns	Constant. Based on ISO 11898-2:2016.
PCB tolerances	-10,0 ns	+10,0 ns	Assumed 2 x 5ns for MCU-TXD and RXD-MCU.
1 time quanta at the receiver (remote node)	24,9 ns	-	Based on clock frequency (assumed 40 MHz).
Worst case sample points (remote sender):	**209,0 ns**	**401,1 ns**	

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Specifications:

- STM32F765NIH6 microcontroller (based on Arm Cortex M7)
- 32 MByte SDRAM in addition to microcontroller RAM
- 6 High-speed CAN channels (ISO 11898-2)
  - Comply with CAN specifications 2.0 A/B and FD
  - CAN bit rates from 40 kbit/s up to 1 Mbit/s
  - CAN FD bit rates from 40 kbit/s up to 12 Mbit/s
  - NXP TJA1043 CAN transceiver with wake-up
  - Alternative pluggable transceiver modules on request
  - CAN termination switchable, separately for each channel
  - CAN connections are D-Sub, 9-pin
- I/O functionality
  - 4 digital I/Os, usable as digital input or output (2 with High-side and 2 with Low-side switch)
  - 1 analog input (0 - 33 V)
- Recording of CAN data and error frames
  - Internal memory: 16 GByte eMMC
  - SD card slot for additional memory
  - USB connection for accessing the data memory (e.g. recorded log data)
  - Conversion of logging data to various output formats using a Windows software
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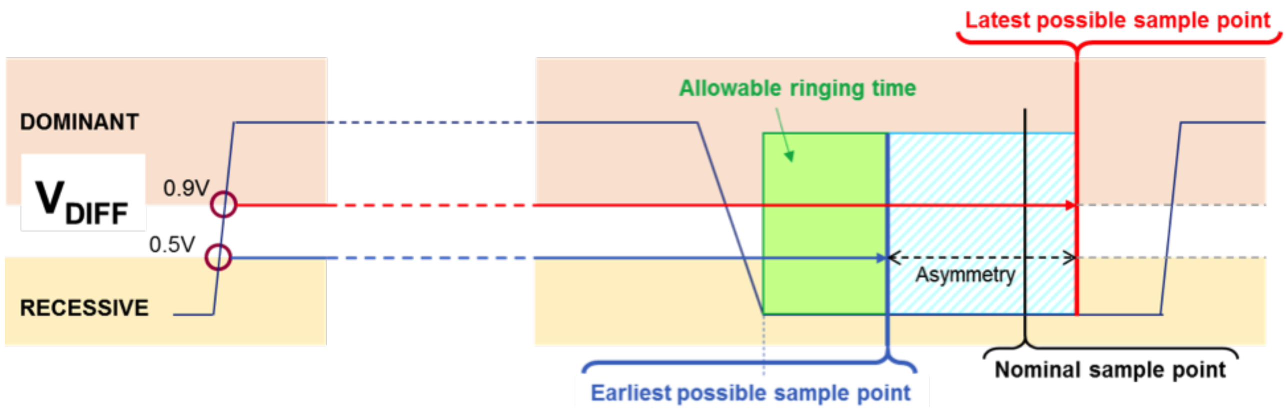

Figure 1: Calculated asymmetries visualized in the recessive bit (Source: NXP)

What can be concluded is a sample point can potentially move much earlier in the bit – at 209 ns in this example (28 % earlier in the bit time vs. the nominal sample point). Thus, for network communication to be robust, its signal needs to be stable much earlier in the bit. Conversely however, we can infer that what happens prior to this earliest sample point is not relevant, as this will never be sampled. This is what we call the allowable ringing time, as any kind of signal distortions here can occur without affecting the network operation.

A complete picture of the full worst case bit pattern with all asymmetries shown is given in Figure 2. The green area demarks the boundary where the CAN signals can safely appear without compromising the network robustness, defined as the "safe operating area". The colors shown in the boxes are the associated contributions from the different components listed in the table above.

The typical worst case simulation

To judge if a network is meeting these criteria and remaining in the safe operating area, a network simulation is normally required to check all cases. In simulation, all possible signal combinations are generated between all possible transmitting pairs and then assessed against the above safe operating area. A complete overview of the communication can be checked to determine if the network is robust or not. If not, the nodes causing the violations can be easily identified. ▷

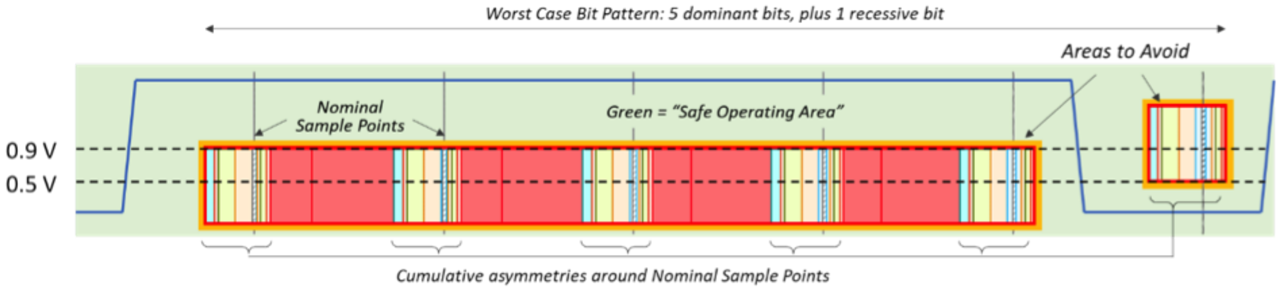

Figure 2: Full visualization of all asymmetries in a worst case CAN FD bit pattern (Source: NXP)

Usually, one would perform a worst case simulation, which uses the worst case parameters stored in the simulation model (selectable in the simulation tool). In our experience however, using this in combination with the worst case timing asymmetries calculated above is not realistic. This is because the worst case simulation model considers all worst case parameters taken from the datasheet, taking each characteristic as an individual potential worst case value, without considering which combination of characteristics are possible at a single moment in time. Furthermore, a transceiver's output driver stability over temperature is much more stable than the datasheet limits are typically predicting.

Instead, our experience leads us to recommend using the typical parameter set in a simulation model, which already gives a very good matching with real world results. The advantage of this approach is not to purely increase the achievable operating space of the network, although this is a desirable benefit. It has the added advantage that simulation results can be easily cross-checked with bench testing, since the simulation conditions used are the same. The margin that would normally be part of the worst case simulation model is now moved into the margin of the safe operating area, since the definition of this contains all worst case asymmetries. Furthermore, the opposite approach can also be taken for those without easy access to network simulation: assessing bench measurements against the same safe operating area can provide a first indication if the network will operate reliably or not. This can simplify early pre-assessments on a network, giving early insights if a topology will operate robustly, and giving confidence when cross-checking simulation results once available.

Factors affecting robust communication

Having now a sound basis for network assessment, we can now look at some common factors that are important in good network design. One of the biggest topics that prevents signals to be stable in CAN FD is signal ringing. Signal ringing is created by impedance changes in the cable harness, for example at cable branches with unterminated stubs. This is not a new artifact and is already present in many Classical CAN networks today, but the bit times are usually sufficient to allow signal ringing to dissipate and avoid any issues in communication.

As CAN FD has much faster bit rates, and consequently shorter bit times, the available time for the signal ringing to dissipate is much shorter, so hence this is one of the most critical parameters to manage from a network design perspective.

The current state of the art is to use a highly linear topology with only a limited number of nodes and short stub lengths, either as a daisy chain topology or in a network of very limited size. This is effective in managing the ringing, but comes with several disadvantages, such as limitations on how cables can be routed between nodes, and likely an associated cable length penalty. In such routing schemes, managing the diversity of networks becomes problematic, if one or more nodes are optional. This may require creating more harness options or deriving more complex (read ▷

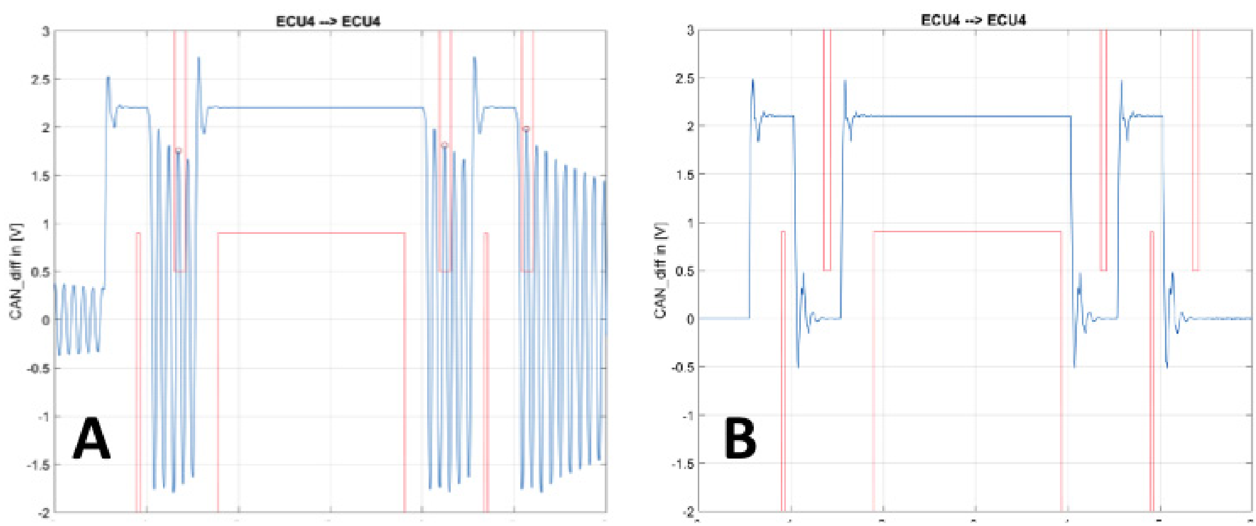

Figure 3: Comparison of signal ringing with (A) conventional HS-CAN transceivers and (B) NXP's CAN SIC transceiver (Source: NXP)

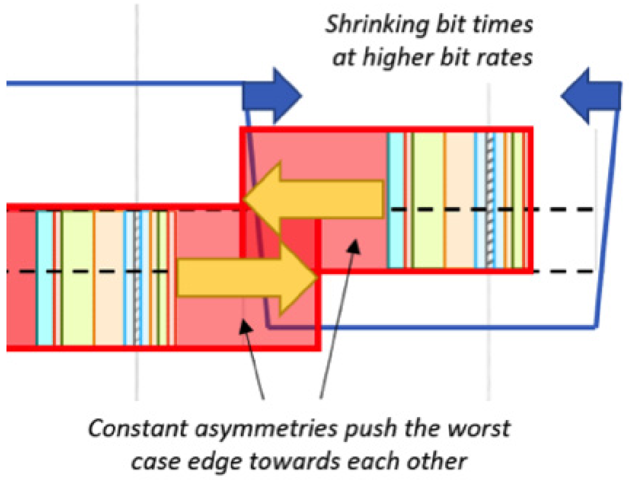

Figure 4: As bit times reduce at faster bit rates, asymmetries become relatively larger part of the bit (Source: NXP)

"expensive") solutions for the harness construction. Additionally, more network branches might be needed to manage the smaller number of nodes per branch.

Many of these problems can be overcome however with the recent innovation of the CAN SIC transceiver, now specified in the CiA 601-4 version 2.0.0 specification.

These transceivers have a dramatic improvement on the signal ringing present in a network and enable network architects to return to complex CAN FD network topologies at higher bitrates. These transceivers offer two primary benefits in their way of working: the signal improvement technique itself and a much tighter asymmetry performance, which will now be reviewed.

Benefits of CAN signal improvement

Figure 3 (A and B) shows two comparative simulation results of a star network of four nodes, a central 60-Ω split star termination and four unterminated stubs of 2 x 5 m and 2 x 0,75 m. Picture A shows the signal with regular high-speed CAN (HS-CAN) transceivers operating at 2 Mbit/s, demonstrating the resultant signal ringing oscillating through the recessive bit. The boundaries of the safe operating area are shown as the red lines, where there are clear violations – confirming, this is not a reliable topology. In contrast, Picture B shows the signal with NXP's CAN SIC transceiver. The signal ringing is brought quickly under control and even this heavily ringing network is able to operate reliably at 2 Mbit/s.

As a general rule of thumb, our experience shows that network topologies already working at 500 kbit/s with regular HS-CAN transceivers will operate with CAN SIC transceivers at 2 Mbit/s and potentially faster, depending on the topology. The rationale behind this is that while it is always possible to engineer a network that will not operate, if standard rules of CAN network creation are generally followed, very large topologies are possible at 2 Mbit/s.

Secondly, we also see that networks validated at 2 Mbit/s with HS-CAN transceivers will generally operate at 5 Mbit/s with CAN SIC transceivers, and potentially faster, depending on the topology. The reason for this is typically 2 Mbit/s networks have reduced levels of signal ringing with HS-CAN transceivers. When CAN SIC transceivers are ▷

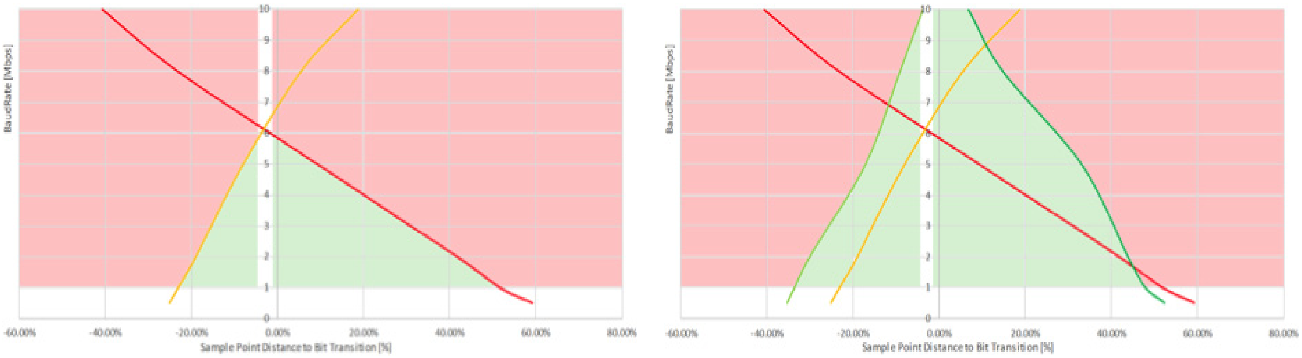

Figure 5: Comparison of the maximum bit rates achievable with HS-CAN transceivers (left) and CAN SIC transceivers (right) (Source: NXP)

applied, there typically needs to be no signal peaks greater than 0,5-V differential voltage at all. This is required since the available margin to the earliest sample point is very limited, so any remaining peaks will typically violate the limits of the safe operating area. Nonetheless, this does not mean that only highly limited topologies can be made with 5 Mbit/s. In the simulation example shown earlier in the article, Picture B shows no peak above the 0,5-V level implying this extreme topology can also reliably operate at 5 Mbit/s with CAN SIC transceivers. This demonstrates that CAN FD operating at 5 Mbit/s is now a realistic proposition for network architects to consider in their network design, where previously this was limited to essentially point-to-point connections.

Tighter asymmetry

The second benefit of the CAN SIC transceiver is its tighter asymmetry performance, briefly covered in our previous article. Using the asymmetry calculations made in the opening section, it can be seen that many of the components of the total calculation are constants and not bit rate dependent. That means that as bit rates increase, the earliest sample point will move further forward in the bit and the latest sample point will move later in the bit (Figure 4). As the bit rates increase, at some point there becomes a collision between the earliest sample point of the recessive bit with the latest sample point of the previous dominant bit, shown in Figure 5. This will define the speed limit for the CAN FD communication, as beyond this point, there is no reliable path from a dominant to recessive bit. Consequently, there is a possibility that a complete bit may be lost, resulting in communication errors.

We can plot this on a graph, showing the position of these extreme sample points on the horizontal axis versus increasing bit rates on the vertical axis to see at what speed they collide.

The left graph (Figure 5) shows these critical edges for ISO 11898-2:2016 compliant transceivers, based on the 5 Mbit/s bit timing specifications. Here it can be seen that the latest possible sample point in the dominant bit (shown as the yellow line) and the earliest possible sample point in the recessive bit (the red line) collide just above 6 Mbit/s. This becomes the theoretical limit of robust CAN FD communication.

CAN SIC transceivers offer a significant improvement on the ISO 11898-2:2016 specification in terms of the required transceiver symmetry. Table 2 shows a comparison table between these two values. The effect is that the earliest possible sample point is now much later, reducing the overall asymmetry. The right hand graph in Figure 5 shows the effect on the earliest and latest possible sample points for CAN SIC transceivers, overlaid with the calculation of the HS-CAN transceivers for comparison. This shows a path from the dominant to recessive bits remains available far beyond 5 Mbit/s and even extending beyond 10 Mbit/s.

As an aside, some HS-CAN transceivers on the market are already claiming 8 Mbit/s operation in their datasheets. User judgment is recommended in assessing whether the stated values quoted in these datasheets are sufficient to reliably meet the maximum bit rate in all conditions or not.

Sample point selection

One choice also worth mentioning in this study is the sample point selection, particularly for faster bit rates, ▷

Table 2: Comparison of asymmetries for ISO 11898-2:2016 compliant transceivers and CAN SIC transceivers (Source: NXP)

	ISO 11898-2:2016 compliant transceivers		CAN SIC transceivers, defined in CiA 601-4 version 2.0.0	
Parameter	**Earliest**	**Latest**	**Earliest**	**Latest**
Oscillator drift	-16,1 ns	+16,1 ns	-16,1 ns	+16,1 ns
Asymmetry of sender's transceiver	-45,0 ns	+10,0 ns	-10,0 ns	+10,0 ns
Asymmetry of receiver's transceiver	-45,0 ns	+15,0 ns	-20,0 ns	+15,0 ns
PCB tolerances	-10,0 ns	+10,0 ns	-10,0 ns	+10,0 ns
1 time quanta at the receiver (remote node)	24,9 ns	-	24,9 ns	-
Worst case sample points (remote sender):	**209,0 ns**	**401,1 ns**	**269,0 ns**	**401,1 ns**

which is slightly different compared with the normal sample point selection at slower speeds, e.g. 2 Mbit/s.

At 2 Mbit/s, the sample point should be later in the bit to allow maximum time for ringing. This is normally chosen around 70 % with standard HS-CAN transceivers, but could be delayed even to 80 %. The approach of delaying the sample point to boost the available topology space as much as possible is still recommended and a move to an 80 % sample point would provide the maximum time for ringing, even with CAN SIC transceivers.

At 5 Mbit/s however, as noted above, any ringing remaining above the 0,5 V is likely to already touch the boundary of the safe operating area, so shall be avoided completely. Accordingly, it is no longer necessary to delay the sample point to later in the bit and in fact, moving closer to the middle of the bit is preferred to provide additional margin for jitter effects or PCB (printed circuit board) impacts. As a guideline, we would recommend a sample point of 50 % + 1 tq, which is approximately 55 %.

Please note, this also applies to the secondary sample point as well, which should be set the same as the nominal sample point. Incorrect setting of the secondary sample point is the cause for many support cases of CAN FD networks, providing a latent problem, likely not visible on ECU (electronic control unit) tests. This issue may never arise if operating at lower bit rates, e.g. 2 Mbit/s, but for higher bit rates, such as 5 Mbit/s, this will definitely be encountered. It is therefore vitally important to check the secondary sample point is correctly set to the same as the normal sample point when operating at higher speeds.

Cabling choices

The CiA 601-6 specification provides guidance on creating CAN FD networks and includes the statement in section 8.1.1 that cable impedances should be within 110 Ohms to 140 Ohms. Furthermore, it even gives a cautionary word, “Note – PVC-based wire-insulation material does not meet this requirement”.

This warning is given due to two effects of the cables, namely a greater sensitivity to temperature that can significantly reduce the impedance of the cable, and a higher propagation delay. The impedance change creates a larger impedance mismatch and so accentuates ringing effects in the network, creating a higher reflection peak; the longer propagation time means that peak would arrive later. Please note, the network simulations shown here are made according this guidance.

The effect of CAN SIC transceivers provides some compensation for poorer performing cables however, due to the tighter symmetry, faster recessive edge, plus the signal improvement actively drives the signal towards recessive. Caution is needed however, and the worst case network simulation defined above would not be sufficient to make this assessment, due to the high temperature dependency of the cable. Also, due to the high variance even across different kinds of PVC (polyvinyl chloride) cables, it is highly recommended to cross-check the performance of the specific cable to be used over temperature. However, CAN signal improvement technology can certainly improve the reach of what is possible and in relatively simple networks, PVC cables may be considered.

Conclusions

In this article, the way of confirming if a network topology is robust has been reviewed, showing how assessments based on worst case asymmetry timings can be even used in bench measurements to simplify network assessments. The recent innovation of CAN SIC transceivers shows how CAN FD can move beyond limited networks to large, complex topologies and at faster bit rates, through only using a simple drop-in replacement transceiver.

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