Automated analysis for vehicle communication

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Those who design CAN FD networks for automotive applications know about the advantages of the CAN successor: the new system maintains existing CAN concepts such as bus arbitration, frame identification, event control, etc. in order that specialists familiar with it do not have to deal with new types of strategies. However, the CAN FD development confronts network designers with some additional challenges mainly attributable to the higher bandwidth in the data phase. CAN FD is noticeably more sensitive to unfavorable network topologies, electromagnetic interference sources and influences as well as wrong termination, for instance. In order to realize robust networks, CAN FD designers must thoroughly deal with these effects which primarily take place on the physical layer. This article presents a comprehensive concept which establishes a strict time-related reference between the logical network analysis and the events on the physical layer. This approach enables users to detect errors and their causes at a very early stage of development, to correct them or to take corresponding measures and thus to come to suitable results more quickly.

Essential innovations of CAN FD compared to the previous CAN standard are the payloads extended from 8 to 64 bytes as well as the possibility to switch to clearly higher data transmission rates. The latter has a direct effect on the network physics, for the time slot to transmit every single bit is proportionately smaller and the usual transient response must also be completed in less time. Reduced signal quality can be a consequence. Matters are complicated further by the fact that faster transmission is only defined during the data phase of a frame, whereas the arbitration phase still takes place at a low bit rate at all times. Thus there are constant switching processes during operation which change the network behavior. Switching takes place at the sampling point of the so-called bit rate switch (BRS) bit implemented by the developers of CAN FD for this purpose. The sampling point of the cyclic redundancy check (CRC) delimiter bit, on the other hand, serves to return to the arbitration bit rate.

For network analysis and debugging of CAN FD networks there are numerous established tools available on the market. Basically all of them aim at supporting the user already in the network design phase. These tools usually only work on the logical layer, i.e. they interpret the data coming from the physical layer and are able to match it with the respective application-specific meaning and particularly to detect frame errors. The bits and bytes sent from the CAN FD controllers are summarized in frames which, in turn, represent the application signals of the CAN nodes. Application signals include revolutions per minute, speed or acceleration of e.g. an engine ECU. During testing and integration of a CAN FD ECU, analysis tools provide assistance. These tools help to ensure that the respective node operates within the application-related specification, on the one hand, and that its transmit/receive behavior complies with the rules of the CAN FD specification, on the other hand [1], [2].

Synchronous view of logic and physics

As most tools reduce the monitoring of network physics to the logical layer, they do not permit insight into the actual voltage curves of the line. If the user wants to examine error causes in complex CAN FD networks in more detail or to assess the signal quality, knowledge of the processes taking place on the physical layer is indispensable. In this

case the means of choice is an oscilloscope used to visualize and record these voltages. However, these are usually separate measurement setups which do not provide any synchronization with the tools for logic network analysis. The concept presented here addresses exactly this aspect by using a suitable measurement setup to realize a combination of logical and physical analyses. For this purpose, the classic analysis tool and the oscilloscope are coupled by means of a network interface. The network interface triggers the oscilloscope via a sync line. On the one hand, this ensures a highly precise time reference of the data recorded and simultaneously preserves the network view of the CAN FD controller, on the other hand. Now integrated software - in addition to the logical abstraction of the network communication - directly permits drawing conclusions about the physical source. If a user detects a logical protocol error, he/she can use a corresponding graphics window to see what is happening physically on the network in the meantime and can thus counteract many physical error causes already in the design phase.

Some of the most important triggers for protocol errors are error causes in the ECU, unfavorably chosen network topologies, faulty terminations and EMC problems. One criterion important for the ECU and the controller is the right sampling point within a bit. The network designer must bindingly fix it and set the controllers of all nodes in a network to this bit timing. If a controller steps out of line, so to say, this may result in errors or failure to comply with the specifications. Errors caused by unfavorable network topologies may result from run-time delays due to too long lines and excessive bit rates at the same time, for instance. Branches and too long stubs may result in signal reflections and interference affecting the signal quality. This is indispensable when designing the network and the node arrangement. In many cases, wrong or missing termination is the cause of errors. CAN FD networks must be terminated at both ends using a 120 ohms resistor, the total resistance should therefore be 60 ohms. If termination is missing at one end, the resistance doubles and halves the current flow. EMC problems may occur when the network-line passes close to sources of electromagnetic interference. Strong electric motors, transformers and inverters, for example, have a high interference potential.

Integrated CAN FD test system

The following section describes how a complete roundtrip can be realized in the error analysis with the aid of a tool. Figure 1 shows the data provided to the tool which are logically and physically depicted in a chain. On the left there is the trace window listing the logical frames which are directly linked with the underlying voltage curves on the network depicted in the window in the middle. Any logical frame components, such as their identifiers or checksums, can be mapped on corresponding voltages at equal time intervals. If this view does not provide sufficient information, the user can focus on the bit layer as depicted in the right window. Here he/she may have a closer look at the transmission rate switching points of CAN FD at the BRS and CRC delimiter bits. Signal quality in the network and synchronization behavior of the nodes can be assessed in detail using an eye diagram.

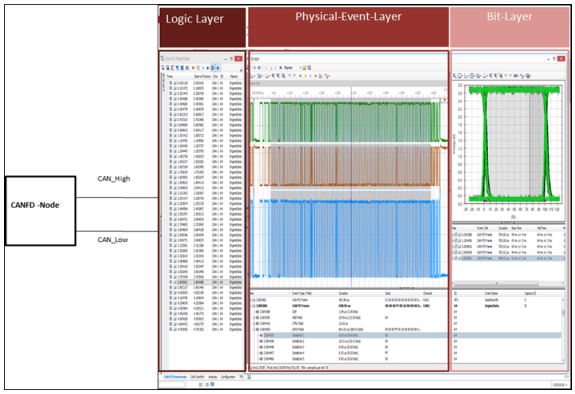


Figure 1: Representation of data in different layers

The decisive advantage of this concept is integrated software which takes the same time base as a foundation for all views. A closed system is useful for this purpose, for it has a high degree of reproducibility. As already implied above, an oscilloscope is most suitable to measure the voltage signals of CAN FD frames. Use a device that can directly be integrated into the analysis tool and synchronized with it in terms of time. Compared to solutions wanting to handle measuring tasks from different contexts and

time bases, the measurement setup described here opens up numerous advantages and opportunities for the developer. They include conformity tests, the generation of eye diagrams, comprehensive bit mask analyses and much more. For maximum utility, extensive test automation may be envisaged eventually serving to perform comprehensive analyses and long-term tests with great testing depth.

Indispensable trigger options

Diverse trigger options in order to reduce the flood of data to essential events and frames are indispensable for efficient analyses. In order to detect protocol errors, the user logically triggers on CAN FD frames indicating the identifier, for instance. Triggering directly on protocol errors - i.e. on CAN error frames - is also useful. Ideally, external signals, for example those coming from an I/O card, can additionally be used as triggers. In principle, two higher-level trigger modes are distinguished - simple triggering on events and cyclic triggering on events. In the first case the tester defines exactly one trigger event to make the system perform exactly one measurement of all events for a defined period of time when the trigger conditions are met. Cyclic triggering means that a measurement is automatically performed at intervals.
Both the standard 11bit IDs and the 29bit extended IDs can be used as triggers. This applies to individual frame IDs as well as to ID ranges. Filters defining which CAN channels the conditions are relevant for are desirable in addition. Figure 2 shows the corresponding configuration window.

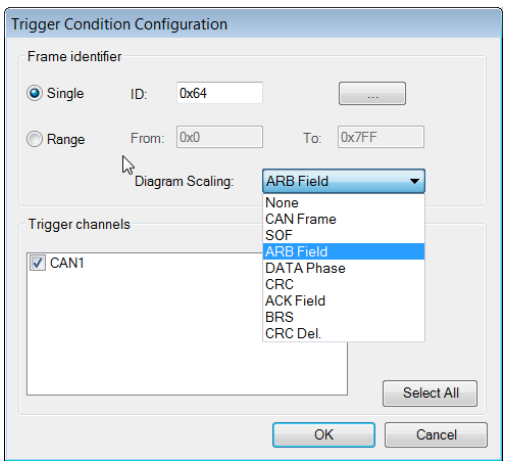


Figure 2: Configuration dialog for CAN/CAN FD frames

When setting trigger conditions it is also very useful to define immediately which bit ranges are to be highlighted in a triggered frame. The options are:

- Complete CAN frame
- Start of Frame (SOF)
- Arbitration field (ID RRS)
- Data field (byte 1…byte n)
- Cyclic Redundancy Check field (CRC, CRC delimiter)
- Bit Rate Switch (BRS)
- acknowledge field (ACK slot, ACK delimiter)

Any available analysis windows automatically synchronize with the selected range.

For a quick view of the current state of the physical layer you may want to have an option to trigger snapshots manually. In this way the user can arrive at a rough assessment of whether communication is taking place at all in the network. If a trigger condition is met, the system interprets any recorded frames according to their logical meaning. The logical frame view is directly overlaid with the physical controller view. In Figure 3 the CAN_HIGH, CAN_LOW and CAN_DIFF signals can be seen. The voltage curve highlighted in color represents the first data byte of a frame including the stuff bit, and has the logical value 0.

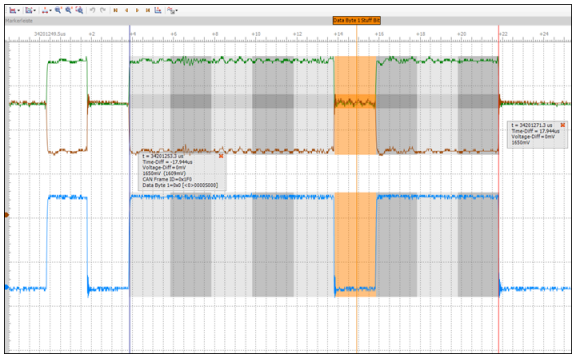


Figure 3: Configuration dialog for CAN/CAN FD frames

Export and import options

In order to repeat analyses in an atomic and reproducible way, corresponding export / import functions for diverse scenarios and measuring configurations are an important prerequisite.

Export and import possibilities would be desirable for the following elements, for instance:

- Measured data with logical interpretation
- Eye diagram with logical interpretation
- User-defined bit masks for CAN/CAN FD
- Voltage curves in CSV or MATLAB format

Analyzing on the bit and byte layer

When a user reaches the limits of working on the logical interpretation of a CAN FD frame, he/she intensifies the analysis on the bit and byte layer. Basically there are two methods available: the eye diagram and the bit mask analysis.

Eye diagrams allow for a detailed view of the network voltage curve for the duration of a single bit. According to the CAN protocol, a bit can be divided into four segments: the synchronization segment, a segment to compensate time delays, and two phase segments. The phase segments are responsible for compensating errors at the bit boundaries. The latter are commonly called TSEG1 and TSEG2, with the boundary between TSEG1 and TSEG2 being defined by the sampling point. The eye diagram is ideally suited to check whether the voltage curve is within the specifications or fails to comply with them. For this purpose it overlays selected bit fields of a CAN FD frame.

Eye diagrams can be generated both during a measurement and after the measurement using the recorded data. An eye diagram recorded during the measurement provides the user with the opportunity to permanently keep an eye on the physical layer and to keep track of any changes. Depending on how robust the network is, the user could modify the network during the run-time and simultaneously observe their effects in the eye diagram.

Eye diagrams for online and offline measurement

Figure 4 contains such an eye diagram: on the left side of the picture, the user can see the voltage curves measured on the network. Below them, all frames are depicted in a tree view, beginning with the SOF through to the IFS (inter-frame space). If the user navigates through the tree, the graphics window always indicates the associated voltage curve. On the right side there is the eye diagram which overlays the bit fields set in the trigger condition. The (so-called) persistence mode of the eye diagram serves to store a lot of measurements in a ring buffer and to display them at the same time. A bit key is located below the eye diagram listing the analyzed bits of all frames. If there are bit edges, the system additionally shows the bit duration for each bit and the time of its rising or falling edge. It determines the edge times between ten and ninety per cent of the voltage swing. The user may select several bits in the key and synchronize them with the voltage curve readouts.

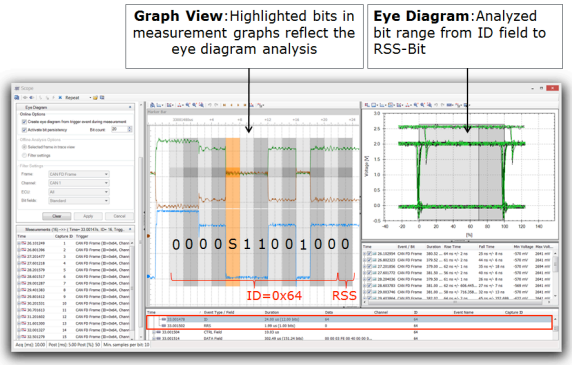


Figure 4: Bits of the arbitration (ID, RTR) as a voltage curve and as an eye diagram

In like manner, eye diagram analyses are possible after a measurement for pre-defined bit fields. Due to the different data rates, the bits of the arbitration phase and the bits of the data phase must principally be distinguished. Since each phase requires controller settings adapted to the transmission speed. For this reason, the offline analysis defines different bit fields for each phase as well as for the corresponding eye diagram.

Using bit masks as a quality criterion

In order to refine the tests, the user can filter frames and their analyses by channels (e.g. CAN1) as well as by ECUs. A particularly valuable function of the eye diagram is the possibility to define special bit masks. They can be added at any time and are free to be designed according to the user‘s demands

and/or the respective network requirements. As the bit mask virtually determines a hard error limit, it permits clear statements on violations. If the voltage curve passes through a mask, this indicates a possible violation of the physical specification. It is useful, for instance, to make the system color any voltage curves with violations red, whereas those without violations of the mask are depicted in green. The developer is provided with diverse illustration facilities, he/she can zoom into masks or have only the red lines with violations of the quality criteria displayed. All bits can thus be visualized with reference to the voltage curves of CAN_HIGH, CAN_LOW and CAN_DIFF. Figure 5 shows a bit mask violation in the eye diagram.

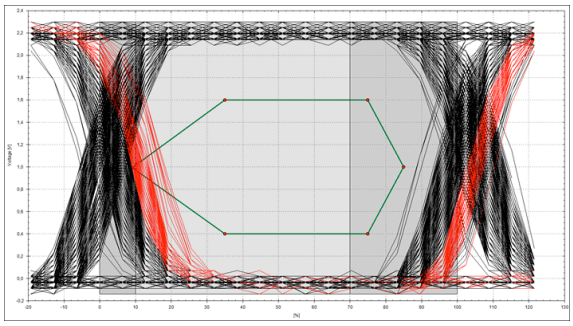


Figure 5: Eye diagram with bit mask violation

The bit mask analysis represents a powerful and scalable tool working in a similar manner. It extends the bit mask display to a complete bit field. Here, too, correct bits are distinguishable at a glance from faulty ones with mask violations as they are colored on the analogy of the eye diagram. Figure 6 shows sequential control and assessment criteria of the bit analysis for the defined bit mask of an analysis performed automatically. Figure 7 describes how to define bit masks for dominant and recessive bits. Finally, Figure 8 depicts the result of an analysis performed.

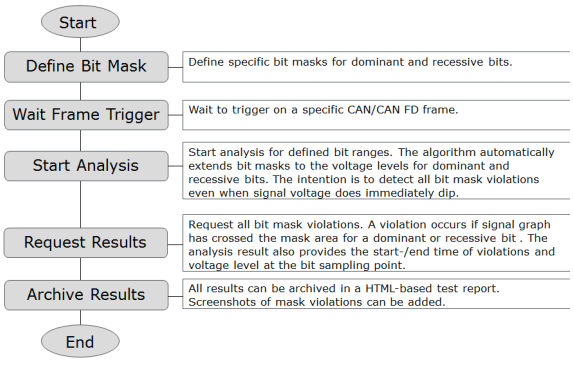


Figure 6: Sequence of a bit mask analysis

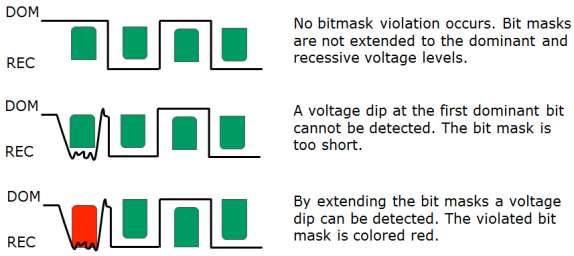


Figure 7: Bit mask definition for dominant and recessive bits

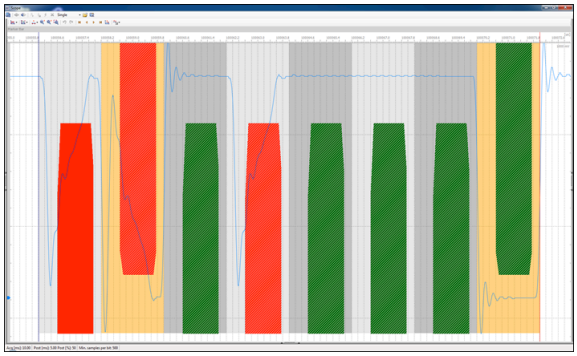


Figure 8: Result of a bit mask analysis

Examples of the analysis of networks

If the user modifies various network parameters, he/she is primarily interested in the effects and, besides, in which controller settings he/she can use to influence the CAN FD network in the best possible way. The following application examples are supposed to demonstrate how the described analyses may look like in practice. In line with the subject of this article, the focus is on the physical layer.

Network termination measuring example

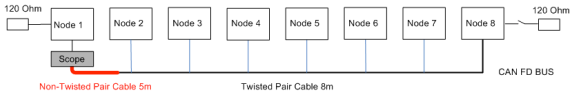


Figure 9: Measurement setup for single-sided and both-sided termination

The first example covers a network test setup comprising eight CAN FD nodes and a total line length of approximately 13 meters (Figure 9). The main network-line consists of a twisted-pair cable, the stub to node 1 is not twisted. Node 3 sends cyclical CAN FD frames while an oscilloscope is connected to node 1. For a start, the network is terminated with 120 ohms on both sides. During the measurement the termination at

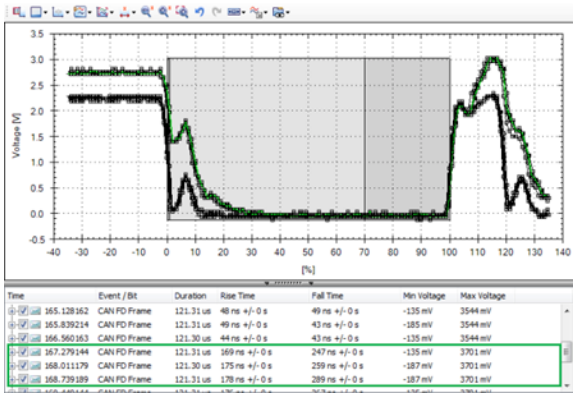
node 8 can optionally be switched on or off. Table 1 shows the settings of the CAN FD controller for the arbitration phase and the data phase.

Table 1: Controller settings for network termination measuring example

	Baud rate	**Sampling point**
Arbitration	500 kbit/s	0.70
Data phase	4000 kbit/s	0.85

Figure 10 shows the results in the form of an eye diagram for different terminations, with a total resistance of 120 ohms, for one thing, and with 60 ohms, for another. The latter results from two 120 ohms resistors connected in parallel. The BRS bit is depicted on the left side, the right side shows a bit of the data phase, with the frame having the ID 300 being selected here. Curves colored in black represent the termination with 60 ohms. Green curves show the effects of single-sided termination with a total resistance of 120 ohms.

Analysis at the bit rate switch (BRS)



Analysis of the data phase

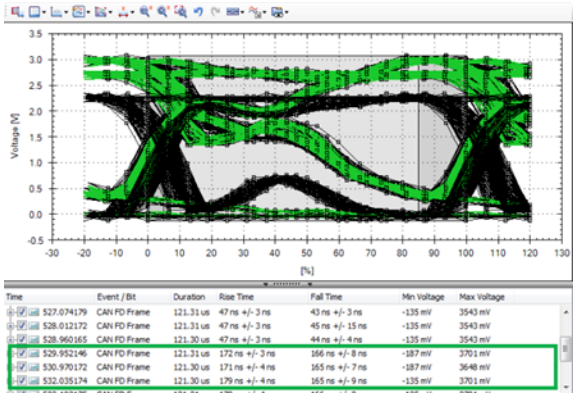


Figure 10: Eye diagrams with different terminations

If both sides are terminated, the network operates at only half of the overall resistance of both-sided termination. The resistance of the entire network decreases and allows for a higher total current. The nodes‘ CAN transceivers can therefore deliver more current, for according to their equivalent circuit diagram they act as a power source. This fact makes itself felt particularly during edge changes of the levels from recessive (1) to dominant (0). From an electrical point of view, they represent rising edges which reach the maximum voltage more quickly. Falling edges, i.e. the level change from dominant (0) to recessive (1), however, can be compared to the discharging process of an RC element.

Here the transceiver does not actively deliver any current; during falling edges it corresponds to a low-pass with the time constant R*C, with R being the total resistance of the network mainly defined by the termination. Consequently, single-sided termination and a larger resistance makes this discharging process take longer than it is the case with both-sided termination. The measured values are listed in Table 2, the values in brackets represent single-sided termination.

Table 2: Measured values for the network termination measuring example

Analysis area	**Sample Point Arbitration**	**Sample Point Data Phase**	**Rise time [ns]**	
BRS	0.7	0.85	48 (175)	
DATA Phase	0.7	0.85	47 (171)	
Analysis area	**Fall time [ns]**	**Duration [µs]**	**Min [mV]**	**Max[mV]**
BRS	49 (259)	1.42	-135 (187)	3544 (3701)
DATA Phase	43 (165)	49.76	-135 (187)	3543 (3701)

The eye diagram and the table reveal that with 85 %, the sampling point for the fast data phase is rather at the end of the bits. It is deliberately selected like this in order that both termination variants provide for functioning communication without ERROR frames. If both-sided termination is consistent, the sampling point can also be set at 70 %. However, in the event of single-sided termination, this selection of the sampling

point did not produce any communication in the tests. The essential conclusion drawn from this analysis is that termination is very important for flawless communication, on the one hand, but that deficiencies in the network can be compensated to some extent by well selected controller settings, on the other hand.

Acknowledge field (ACK) measuring example

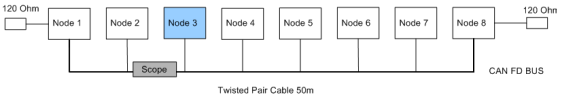


Figure 11: Measurement setup for ACK measuring example

Node 3 cyclically sends the CAN FD frame with the ID 300 again. The network is terminated with 120 ohms on both sides. In this example, the oscilloscope is located directly behind node 3. The length of the connection from oscilloscope to node 8 is approximately 50 meters without stubs of 0,2 meters each. Table 3 lists the CAN FD controller settings for arbitration phase and data phase.

Table 3: Controller settings for ACK measuring example

	Baud rate	**Sampling point**
Arbitration	500 kbit/s	0,70
Data phase	4000 kbit/s	0,85

The ACK slot serves to examine two interesting effects:

1. An increase in the dominant voltage level at the ACK slot bit compared to the level of 2,5 V for dominant bits typical for CAN. As one expects, the level increase is attributable to the fact that all nodes of the network in the ACK slot send a dominant bit (>= 2,5 V) in order to confirm faultless reception of the frame.

2. A time extension of the ACK slot compared to the nominal bit time of 2000 ns. The extension can be estimated in a rough calculation before the measurement is performed.

When using a twisted CAN cable you may approximately assume a propagation speed of roughly 60 % of the speed of light in vacuum.

0,6 x 3 x 109 = 1,8 x 108 m/s ===> 5,56 ns/m

The run-time of a signal supplied by node 3 to the other end of node 8 at a distance of 50 meters is:

T = S / V = 55 m / (0,18 x 109) = 277 ns

The receiver at node 8 transmits the signal to the CAN controller, with the delay depending strongly on the type of receiver. An assumption of 65 ns is an excellent average for typical delays between 50 and 80 ns.

After processing the signal, the CAN controller, in turn, sends the ACK signal for confirmation. In many devices, its delay is in the single-digit nano range, so that 10 ns can be assumed here. You have to add a transceiver delay of 50...80 ns, let‘s assume 65 ns. Further 277 ns elapse on the way back until the signal arrives at node 3 again.

The total delay is approximately ~277 ns + 65 ns + 10 ns + 65 ns + 277 ns = ~694 ns

Therefore the ACK slot is supposed to be extended by approximately 694ns [3].

Figure 12 shows the measurement result. The example furnishes impressive proof of how the theoretical assumptions can be confirmed by measurements using the measurement setup presented. The ACK slot shows an increase in the voltage level of approximately 1 V. The measured values can directly be read from the voltage curves of the CAN FD frames on the left. For reasons of clarity, the measuring markers of the tool were deliberately omitted. The eye diagram on the right reveals the ACK slot extension for a voltage level of 0,5 V (recessive). The additional time span is 33 % of the nominal bit width, corresponding to approximately 660 ns. From the view of oscilloscope and node 3, the total bit length of the ACK slot is 2660 ns.

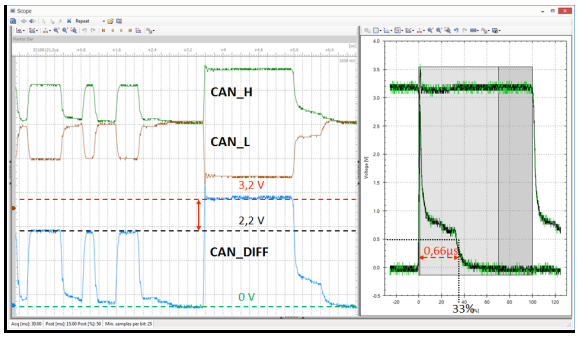


Figure 12: Measurement results of the ACK measuring example

Automating the analysis facilities presented

In complex measurements and tests, being able to draw on a dedicated test environment is invaluable for the developer. Accessing the oscilloscope by program or processing script is also possible in that case. The above-mentioned measurement methods can simply be automated by allowing the user to define test cases. Whereas one test case analyses the data phase of all CAN FD frames, for instance, another one examines their arbitration phases. Conformity tests for an ISO-compliant transmission of frames are also included. After the tests, the user must be able to comprehend for which reason a certain test case has failed, for example. A specific test criterion must therefore be determined for each test case. The criterion could be the bit timing settings of the controller, for instance, with different sampling points for both phases. Another suitable test criterion is a bit mask for the eye diagram which indicates if it is violated by the signal curve. Ideally a tool-specific programming interface serves to create special user-defined test scenarios for the eye diagram and the serial bit mask analysis. This allows for comprehensive reports with snapshots of the network physics after each test. All the test cases can automatically be processed and assessed in succession, and the results can be saved in a separate test document. Test reports can be designed individually. Principally, different methods are suited to automate the tests. Simple sequential control is possible as well as automation via a programming interface.

Conclusion

The analysis concept presented here provides the developer with almost unlimited opportunities to optimize the design and error analyses of CAN FD networks. A special feature is the synchronous display of logical and physical views of the network events. Options range from online analysis to complex, automated and program-controlled test runs. Basically, the procedures described are not limited to CAN but could also be applied to other networking systems.

References

[1] ISO11898-1:_ Data link layer and physical signaling
[2] ISO11898-2: High-speed medium access unit
[3] http://www.itwissen.info/definition/lexikon/Signalausbreitungsgeschwindigkeit-signal-propagation-speed.html

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