The FlexRay Electrical Physical Layer Evolution

The final version 3.0 of the Electrical Physical Layer Specification was published recently. It is the final deliverable set of specifications for the FlexRay Physical Layer. The FlexRay Consortium has worked over nine years to create this FlexRay standard for In-Vehicle Automotive networking.

The version 3.0 became an unambiguous description of the physical layer and closes gaps in the 2.1 version. The majority of the changes have been introduced to guarantee full performance of a FlexRay system also at the limits of operation. Requirements from the Japanese market are taken into account in order to create a worldwide standard. It is expected that the forthcoming transfer of the FlexRay 3.0 specification into an ISO standard will cause no technical changes.

In version 3.0, additional measures for signal integrity were introduced to have an unambiguous definition of reliable network topologies. The interoperability with former specifications (Electrical Physical Layer and Protocol) is kept throughout version 3.0 of the EPL specification.

The FlexRay consortium has recently published version 3.0 of the Electrical Physical Layer Specification (EPL). The previous versions 2.1 Revision A and Revision B showed some lack of specification and room for improvement. Even though many of the new features and more specific timing requirements are already provided by some EPL 2.1 compliant products, the EPL 3.0 standard ensures to have these in every product in the future. Therefore, version 3.0 can be seen as natural progression, with improved system behavior while keeping characteristics of the Physical Layer unchanged. Additionally, the Electrical Physical Layer Application Notes (EPLAN) of the EPL 3.0 have been expanded to give valuable information for the implementation of FlexRay systems.

Major advantages of EPL 3.0 and EPLAN 3.0 compared to the previous version:

- Signal Integrity (SI) voting and changed eye-diagrams provide an unambiguous assessment of signal integrity and thus reliable topologies
- The more restrictive specification of asymmetric delay related parameters avoid unnecessary limitations of possible topologies
- Tightened parameters, e.g. TxEN timeout, perfect the system behavior, e.g. faster exclusion of babbling idiots
- Newly introduced parameters, e.g. idle loop delay, are needed to rely on system behavior, e.g. guarantee a proper start-up even at the limits of operation
- Wake-up via frames allows a bandwidth-optimized wake-up during operation
- Full description of the active star guarantees reliable interaction with FlexRay Communication Controllers, e.g. timeouts and error confinement
- Alignment with Japanese requirements provides a worldwide standard and a strong basis for becoming an ISO standard
- Compatibility with former FlexRay EPL versions allows heterogeneous networks, e.g. interoperability of new ECUs with already existing ECUs

This article gives an introduction of the technical changes, the motivation for changing and the consequences of such changes as well as the interoperability between the different versions.

From plug-and-play to signal integrity focus

With EPL 2.1 the intention was to have all topology parameters, e.g. cable attenuation, cable length, and number of nodes limited in order to allow a "plug-and-play" network implementation. It has been proven that it cannot be guaranteed that all possible combinations of the specified parameters provide a reliable network topology. Nevertheless, the probability is high to find a suitable combination in this solution space.

A definition of a universal network topology would have caused an enormously constrained topology freedom. Therefore, the original approach was changed and, with EPL 3.0, the focus is now set to signal integrity guaranteeing appropriate decoding at receivers. Unnecessary limitations are removed to allow more flexibility, e.g. a cable with a

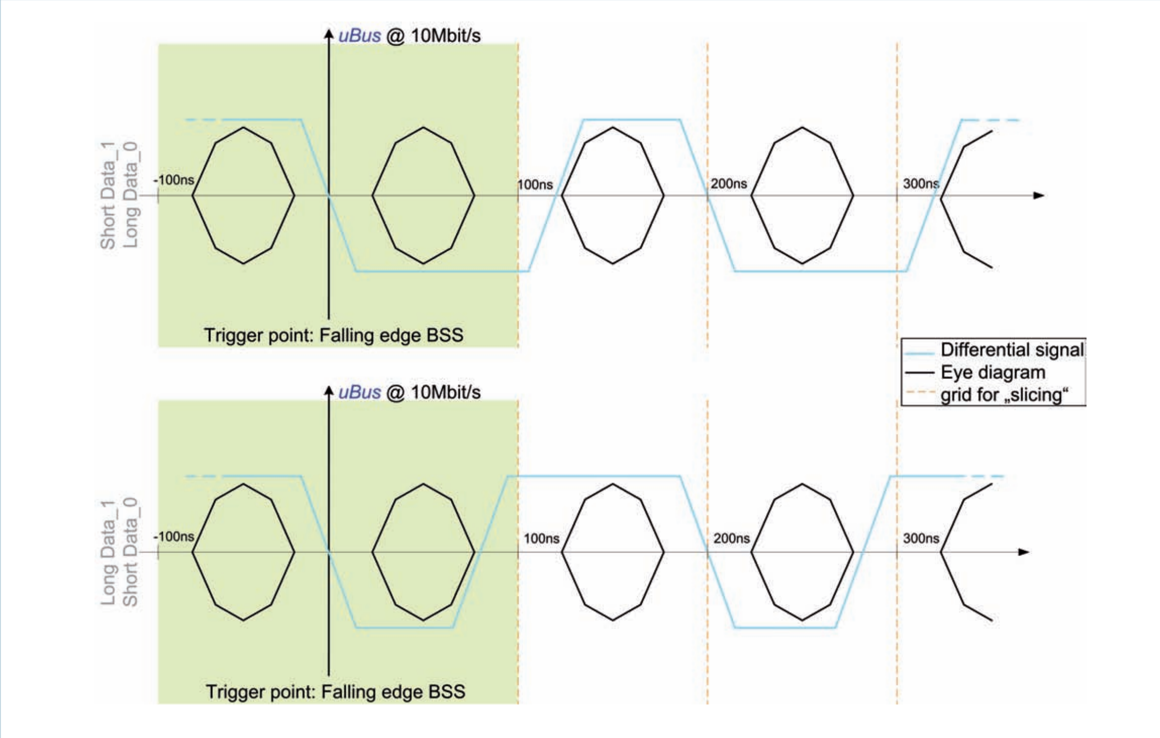

Fig 1. Eye-diagram capture method

high attenuation could fulfill signal integrity requirements as long as the cable is short enough. Regardless of the changed definition, the former limits are not binding, but still give a sound orientation for the development of the system.

Measures for the signal integrity

With this new approach, measures are needed for signal integrity with a clear distinction between contribution of the device and contribution of the network. The EPL 3.0 includes several timing and voltage level requirements for the assessment of transmitter and receiver of physical layer devices, guaranteeing a minimum output signal. Whether or not a physical layer device fulfils these requirements is tested in the conformance test. To provide additional physical measures for the devices, mask tests have been introduced to summarize the transmitter output requirements.

As measure for the quality of the network and for the validation of different topologies, two methods are now included in EPLAN 3.0.

The eye-diagrams, previously included in the EPL, have been shifted to EPLAN. The definition of the eye-diagrams and the method how to capture are adapted in order to include the requirements of the time triggered behavior. For the synchronization of the nodes in the network, the FlexRay data frame includes byte start sequences (BSS), a Data_1 and Data_0 sequence, which is transmitted prior to each byte. The capturing of the eye-diagrams is synchronized with the falling edge of each BSS similar to the way in which the FlexRay receiver works. The falling edge of the BSS is the trigger condition for the following eight bits, which are sliced into single bit segments, are overlaid for the eye-diagram (**Fig. 1**). With this definition of the eye-diagrams, the consideration of the minimum bit duration is implicitly included. For the different data rates dedicated eye-diagrams are now available to consider the resulting differences of the decoder's minimum timing requirements.

Differently to CAN (Controller Area Network) with one receiver-threshold, the FlexRay Physical Layer has defined two receiver-thresholds, distinguishing three states on the bus wires: Data_0, Data_1 and Idle. This provides a certain robustness against ringing effects, which is not completely considered in the eye-diagram. A differential signal that violates the eye-diagram must not necessarily cause a decoding error (**Fig. 2**). To overcome this over-strictness, SI voting has been introduced. The SI voting is a mathematical procedure that simulates the behavior of a receiver to judge whether the network meets the signal integrity requirements. It includes the maxima of the variation of the thresholds, the mismatch of Data_1/Data_0 thresholds as well as the idle detection time. SI voting finally judges whether the resulting RxD signal shape allows fault free decoding. Today, the SI voting procedure is implemented as function in specific oscilloscopes.

A fail in the eye-diagram test respectively in SI voting, indicates a problem in the network, which concerns the topology and network parts (cables, connectors, chokes, PCB, etc.).

Beside these two physical measures, the simulation of the network behavior is highly recommended as an additional tool for defining the right topology.

Optimized timing behavior

The FlexRay protocol has certain timing requirements, which, have to be fulfilled by the Physical Layer. Most critical is the asymmetric delay budget of the signal path from

the signal source (protocol engine in the transmitting Communication Controller (CC)) via the network to the signal sink (protocol engine in the receiving CC) to guarantee a proper decoding of the data stream. The asymmetric delay budget describes the maximum allowable bit-deformation (lengthening or shortening) that can be accepted by the decoder. The bit-deformation is caused by different propagation delays of the rising and falling edges.
In EPL version 2.1 the description of the Physical Layer ended with the digital in- and outputs of the Bus Driver (BD). Due to this, several important parameters of the interface between BD and CC are expected to be missing in most datasheets of EPL 2.1 compliant products and a reliable worst case calculation of this interface is not possible.
With EPL 3.0 there is a description of the complete signal path consequently realized with improvements at several network parts, especially the interfaces between devices (**Fig 3**).
The signal path diagram now includes requirements for all components between the transmitting and the receiving protocol engine, e.g. the CC and the BD-CC interface. The BD-CC interface (TxEN, TxD and RxD) is clearly specified with thresholds, output levels, rise- and fall times and load conditions. The EPL 3.0 includes some extra requirements to ensure proper communication for ECUs with long distances (>15cm) between CC and BD. Based on these definitions, the worst case calculations for the different asymmetric delay portions were performed for different topologies. The related figures can be found in chapter 6 of the EPL 3.0.
A worst-case calculation of the path from transmitting BD to receiving BD was already possible with EPL 2.1, but due to the lack of stringent requirements the results were often too pessimistic associated with unnecessary limitations for the topologies. In EPL 3.0, the test conditions of the transmitter and receiver requirements are tightened from only one test signal to a complete signal range. This, together with some new parameters, guarantees a proper timing under all circumstances and allows an improved worst case calculation for each topology. A detailed description of the network requirements and signal timing calculations for several topologies can be found in chapter 3 of the EPLAN 3.0.
The interaction with the FlexRay Protocol Specification (PS) and the general system performance were improved by several changes of existing system parameters and by introducing new parameters. For example the decreased limit of the TxEN timeout is limiting the effect of erroneously permanent transmitting nodes ("Babbling Idiots") and the newly introduced "Idle Loop Delay" is needed to guarantee a proper start-up of the system.
Other timing parameters were introduced to have fixed values for standardized drivers (e.g. AUTOSAR), mode transition time and undervoltage recovery time are just two examples.

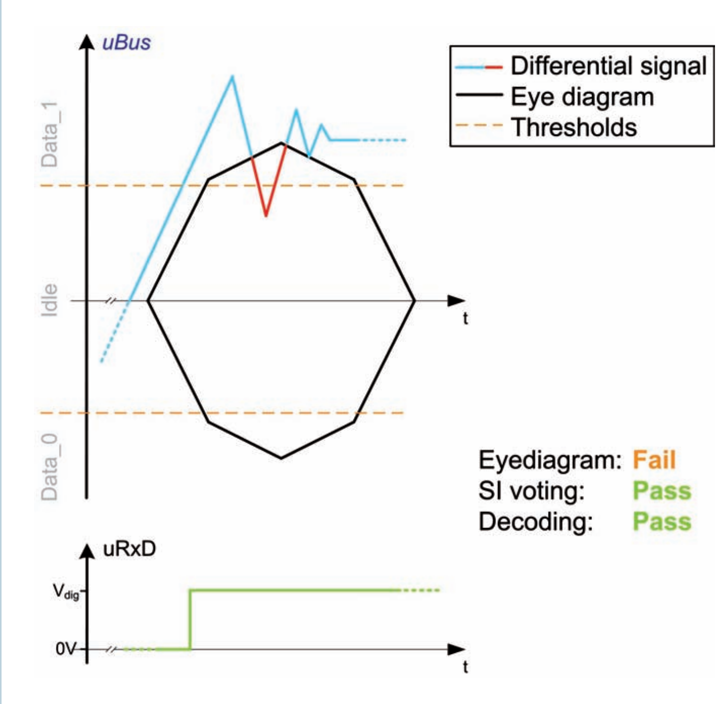

Fig 2. Example SI voting

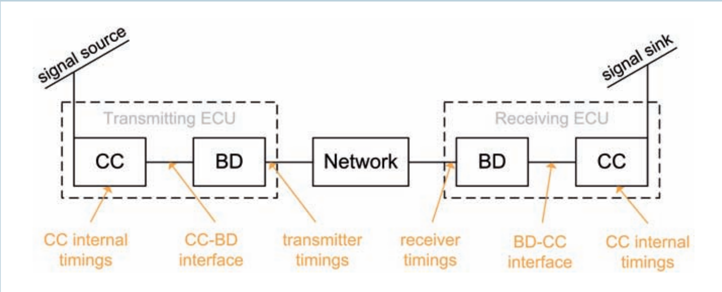

Fig 3. Simplified signal path diagram

Wake-up during operation

The wake-up pattern for remote wake-up of bus drivers or active stars via the FlexRay network was already defined in EPL 2.1 Revision A, but its description is now more precisely and unambiguously documented in EPL 3.0. Additionally, the description of the wake-up detector requirements is enhanced with a detailed picture of an exemplary wake-up state machine. This new description prevents incompatible implementations of the wake-up receiver and ensures reliable detection of wake-up events.
The normal wake-up pattern will be sent during the start-up procedure before the network is synchronized. This is sufficient as long as all nodes and active stars stay awake. In some cases, the nodes shall be woken up, again, during operation (after the synchronization), as normal communication on the bus does not guarantee a wake-up of the nodes. One solution is to send the wake-up pattern in the symbol window. However, this symbol window allocates a lot of bandwidth and is therefore often not configured. To overcome this, the EPL 3.0 describes a dedicated payload for wake-up

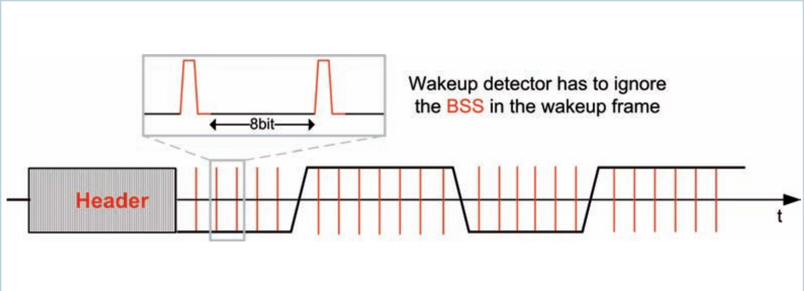

Fig 4. Wake-up via frames for 10Mbit/s data rate Active St

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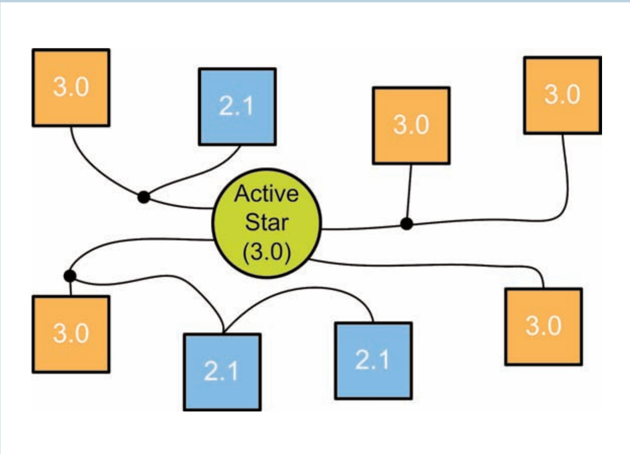

Fig 5. Exemplary active star application

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via frames. This payload can be transmitted as a normal payload in any data frame, without especially reserved bandwidth. The Byte Start Sequences (BSS) in the frame are ignored by the wake-up detector due to its limited receiver bandwidth and thus such a frame is recognized as a wake-up pattern (**Fig 4**). Wake-up via frames is only defined for systems with 10Mbit/s data rates, as for lower data rates the BSSs become too long for being suppressed.

Almost all FlexRay topologies of current car implementation use active stars. The active star allows connecting a high number of nodes in a network by keeping the signal integrity at a high level. The error confinement capabilities are able to isolate erroneous branches while continuing communication on the rest of the remaining network. In consequence of its functionality, the active star is a central element in the network (**Fig 5**) and therefore a reliable behavior is here even more needed. This was not fully enforced by the EPL 2.1, as the active star behavior was outlined only. In EPL 2.1, the bus driver requirements are described on 30 pages, whereas the more complex active star was described on only 12 pages, just giving an impression. This lack of specification allows many different implementations which might differ especially in the error confinement. Consequently, the assessment whether the device meets the protocol requirements needs to be performed individually for each device.

With EPL 3.0 the active star chapter is completely reworked, resulting in a comprehensive and unambiguous specification. Additional timing parameters were introduced and correlations were exploited for reducing the ranges of existing timing parameters. The optimized timing parameters facilitate the protocol constraints, allowing a more efficient parameterization of the protocol. Several improvements (e.g. error confinement and under-voltage behavior) were included to optimize and standardize the functional behavior. Operation mode descriptions and the transitions between these modes are adapted to clearly specify the optimized active star power modes. Additional branch states and branch state transitions clearly specify the active star's behavior in case of wake-up, start-up and normal communication as well as in case of errors , which is strongly required for an optimized error confinement in the network. Detailed and uniquely defined interfaces to the CC and the host controller guarantee the needed timing and functional requirements.

JASPAR

The JASPAR (Japan Automotive Software Platform and Architecture) consortium made investigations for defining a set of topologies and their own subset of the Electrical Physical Layer Specification. Initially, the JASPAR specifications included more restrictive requirements and its own conformance test. The collaboration of the different working groups from both JASPAR and FlexRay resulted in a clear and common specification, the: EPL 3.0 and the corresponding FlexRay Physical Layer Conformance Test 3.0. This enables the semiconductor manufacturers to build a single device that serves a global market.

The measurement conditions of several parameters as well as some descriptions of the error confinement were clarified or adapted. The functional classes "Bus driver/Active Star increased voltage amplitude transmitter" reflect the Japanese requirement of 900mV minimum transmitter output voltage. This is needed to meet the eye-diagram in JASPAR topologies. The need for rethinking the definition of the eye-diagrams and introducing the mask tests was triggered by these discussions.

Last but not least, the conformance test specification was supplemented by several dynamic test cases completing the functional test coverage. The Japanese partners also accepted to test many of the parameter values by chekking the datasheet values, the so called "static test cases".

Interoperability of different EPL versions

The central question that arises with all the mentioned changes is the interoperability of the different Electrical Physical Layer Specification versions. The different EPL versions are interoperable.

The key factor for the interoperability of different physical layer devices in one FlexRay network is the interaction of the devices with the bus. This is mainly determined by the more restrictive behavior of the transmitter and the receiver. In EPL 3.0 the requirements are described in more detail, whereas the behavior remains unchanged.

The following examples of the major changes give an overview how changes effect the communication. The lower limit of the transmitter slopes is increased for a better EMC behavior and for reducing ringing effects. The advantage is that the resulting range of transmitter slopes is a subset of the previous versions and does not require changes in the receiver. Same is valid for the newly introduced maximum mismatch of the slopes. If it works without this limit, it will work for sure with the more restrict requirements of the transmitter. However, the additional new limits improve the results of worst case calculation of the asymmetric delay from sending to receiving CC.

With the functional classes "Bus Driver/Active Star increased voltage amplitude transmitter", the minimum of the differential output voltage can optionally be increased to ±900mV, while the maximum limit remains unchanged at ±2000mV. It should be noted that, for FlexRay transceiver implementations, the typical transmitter output voltage will only increase slightly, as the typical value of current available devices is already around ±1000mV. However, it increases the worst case margin between minimum transmitter output voltage and the minimal required receiver signal amplitude (**Fig 6**). Topologies with long distances or many stubs will benefit from it.

As the receiver is unchanged, devices with and without implementing this functional class can operate concurrently in the same network. The limiting factor is the signal integrity, which can be assessed with the eye-diagrams or SI voting as described above.

For the improvements in the receiver specification, the situation appears similar. All changes do not influence the behavior or parameters but tighten the operating conditions. The receiver test signal described in EPL 2.1 is included in the test signal range of EPL 3.0, therefore interoperability is automatically given.

Interoperability with different protocol versions

The EPL 3.0 is designed to make maximum use of the Protocol Specification 3.0 (PS). The interfaces and timing parameters as well as the functional behavior are defined for this combination. They are the basis for protocol constraints and worst case calculations.

Nevertheless, the EPL 3.0 compatibility with a PS 2.1 compliant CC is still given. The applied changes of the functional behavior of the physical layer are seen as evolutionary adaptations. A bus driver compliant to EPL 3.0 automatically exceeds the EPL 2.1 requirements. Therefore, the interoperability with a PS 2.1 compliant CC is as good if not better as with an EPL 2.1 bus driver. An advantage is that the EPL 3.0 compliant bus driver provides all necessary interface definitions. As the interface description of a CC compliant to PS V2.1 does not automatically fulfill the FlexRay 3.0 interface requirements, the asymmetric delay of this interface between the CC the BD needs to be calculated individually. Information about the timing calculation can be found in EPL 3.0 and EPLAN 3.0.

For the other way around, an EPL 2.1 compliant bus driver with a PS 3.0 compliant CC, interoperability is only given when the device specification of the bus driver already provides the necessary parameters for re-calculating the protocol constraints and the signal path timing. As EPL 3.0 devices will be available earlier than V3.0 compliant CCs, the combination of a EPL 2.1 bus driver with a PS 3.0 communication controller is expected to be used rarely.

For active stars compliant to EPL 2.1, the interoperability with any version of the protocol needs to be checked for each device individually on basis of its datasheet and application notes. This is because the EPL compliance is not sufficient to guarantee proper operation. The different combi-

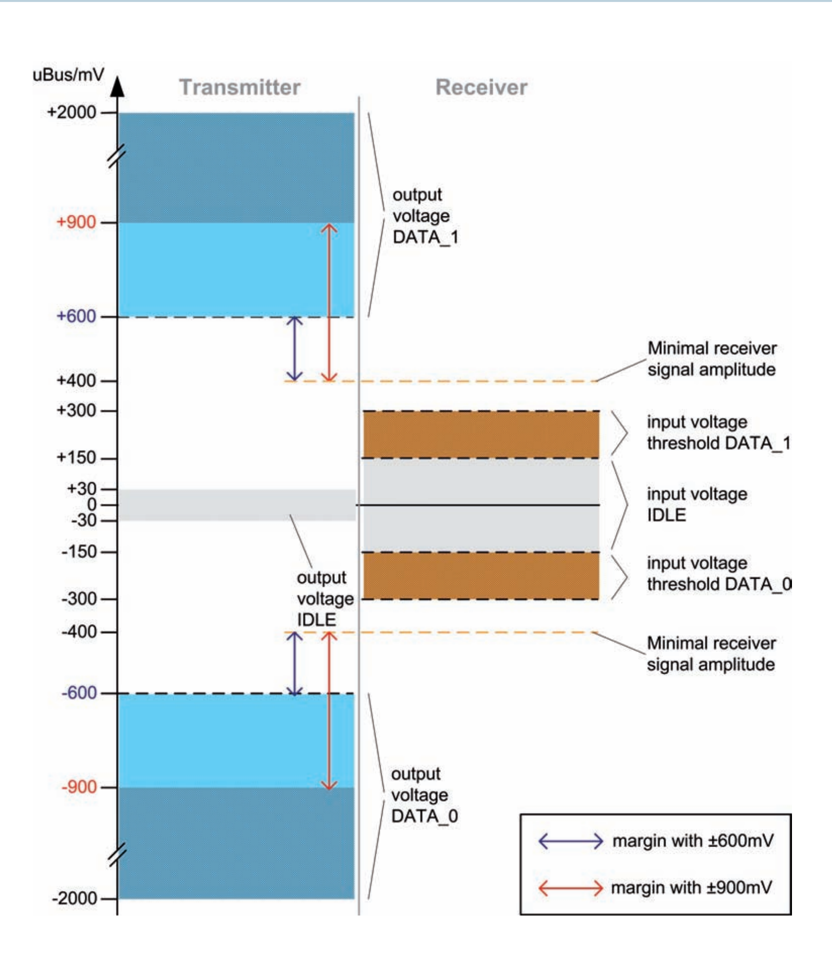

Fig 6. Transmitter and receiver levels

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BD	CC	Comment to interoperability
2.1	2.1	■ Bus driver does not automatically provide all necessary parameters and features (to be chekked in product documentation) ■ BD-CC interface not sufficiently defined (timing calculation to be performed individually)
2.1	3.0	■ Bus driver does not automatically provide all necessary parameters and features (to be chekked in product documentation) ■ BD-CC interface not sufficiently defined (timing calculation to be performed individually) ■ Some 3.0 protocol features are not applicable
3.0	2.1	■ Bus driver provides all necessary parameters and features ■ CC part of the BD-CC interface not defined (timing calculation of EPLAN 3.0 to be modified to actual CC values)
3.0	3.0	■ Bus driver and BD-CC interface unambiguously defined, timing calculation given in EPLAN 3.0

Table 1: Interoperability of different BD and CC versions

nations of BD and CC are summarized in Table 1.
For the reusability of existing ECUs, the configuration of a CC, compliant to PS 3.0, allows to operate in heterogeneous networks with CCs compliant to PS 2.1. However, the full enhanced feature set of PS 3.0 will only be available in homogeneous PS 3.0 networks.

Anything else?

Many small adaptations were applied in EPL 3.0 for improving the standard by making wordings unambiguous. Therefore, dealing with all these changes is out of the focus of this article, and only representative examples are given. Clear requirements for ESD robustness and different temperature classes have been included. Already with EPL 2.1 Rev. B the description of the ERRN pin was extended by the wake-up indication in low power modes. Finally additional ERRN timings were introduced in EPL 3.0.
To simplify the implementation of FlexRay networks, the EPLAN 3.0 includes many new application hints, e.g. the consideration of ringing effects.

Conclusion

Version 3.0 of the FlexRay Electrical Physical Layer Specification, with its enhanced functionality and parameter set in combination with the updated FlexRay Physical Layer Application Notes, simplifies the development of reliable FlexRay communication networks. A device that has successfully passed the 3.0 conformance test automatically provides the needed functionality. Together with 3.0 compliant CCs, the complete enhancement of the devices can be exploited.
The EPL 2.1 compliant NXP products such as TJA1081 and TJA1082, already provide the most important EPL 3.0 parameters and features, e.g. idle-loop delay and wake-up via frames, and therefore a change to EPL 3.0 devices is not needed. However, as these features are not guaranteed for all available 2.1 physical layer devices on the market, it needs to be assessed individually.
For new active star applications it is highly recommended to use 3.0 compliant devices, like the TJA1085, as only with EPL 3.0 the required active star behavior (e.g. error confinement) and timing is guaranteed.
The interoperability allows to combine several devices, compliant to different EPL versions, in heterogeneous networks (e.g. for integrating ECUs with EPL 3.0 compliant active stars into an existing network).
With the eye-diagram and the SI voting, the EPL 3.0 provides two measures for the assessment of the signal integrity in order to determine reliable topologies. Additionally it is recommended to assess the topologies by simulation. NXP is the first semiconductor supplier offering dedicated simulation models as a customer service for their FlexRay transceiver portfolio.
With EPL 3.0 the specification became stricter and products of different suppliers will be more similar with respect to FlexRay functionality. Finally, major product differentiators are product quality and reliability, documentation, EMC/ESD performance, standby/sleep current consumption and additional features as well as the customer support.
As a next step, the FlexRay specifications will be transferred to the International Organization for Standardization (ISO) to become an international approved ISO-standard. As the specification already has reached a high quality, it is expected to have no functional changes within the ISO process.

For the related specification documents please refer to *www.flexray.com.*

List of abbreviations

AUTOSAR	*AUTomotive Open System ARchitecture*
BD	*Bus Driver*
BSS	*Byte Start Sequence*
CAN	*Controller Area Network*
CC	*Communication Controller*
ECU	*Electronic Control Unit*
EMC	*ElectroMagnetic Compatibility*
EPL	*FlexRay Electrical Physical Layer Specification*
EPLAN	*FlexRay Electrical Physical Layer Application Notes*
ESD	*Electro-Static Discharge*
JASPAR	*Japan Automotive Software Platform and ARchitecture*
PCB	*Printed Circuit Board*
PS	*FlexRay Protocol Specification*
SI	*Signal Integrity*

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