Considerations on Functional Safety of the PSI5 Interface in the Scope of the ISO26262

part 1 – presentation
part 2 – paper

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Considerations on Functional Safety of the PSI5 Interface in the Scope of the ISO26262

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The Presented Results are Output of a Joint Collaboration Work within the PSI5 Consortium

For more information see http://www.psi5.org

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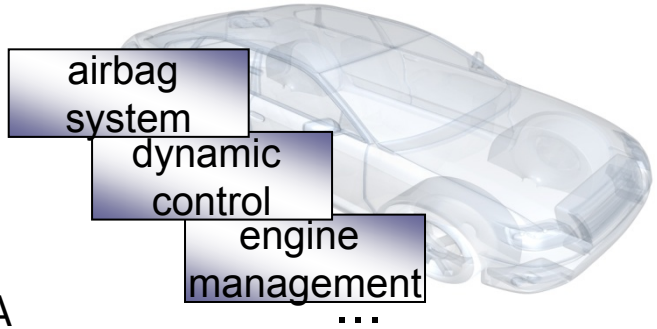
PSI5 – Data Interface for Safety Applications

- 2004: Foundation of the PSI5 consortium
- Original scope: airbag sensor interface
- Main focus:
  - ⇨ data reliability (safety electronics!)
  - ⇨ take the best of the existing protocols
    PAS3/4, PEGASUS, MERAS, RSU, MRSA
  - ⇨ failure prevention is better than failure detection
  - ⇨ cost-efficient implementation



- Status
  - PSI5 has been established world-wide for Airbag applications
  - extension of PSI5 specification for a wider field of applications, e.g. for engine management, dynamic control → PSI5 v2.0
- Foundation of working group „functional safety“ in 2010:
  conformity considerations regarding ISO26262

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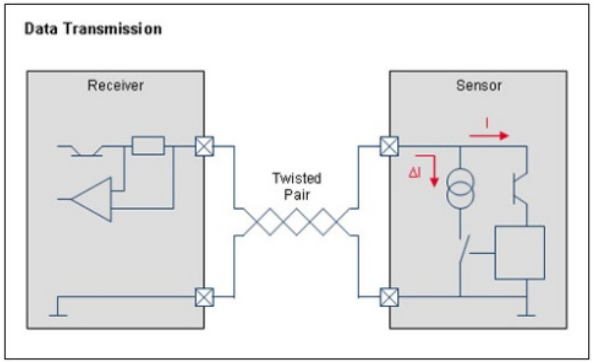
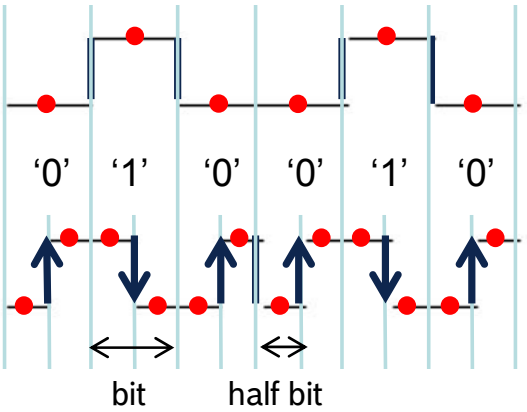
PSI5 – Data Interface for Safety Applications

Several measures for data reliability

- Simple robust circuit
- Twisted pair cable (recommendation)
- Large SNR (determines „raw failure rate“)
- Manchester encoded signal
  (corresponds to full redundant data transmission)
- Pre-defined start and stop (gap) bit pattern
- Protection by parity or cyclic redundancy check
- Start-up phase: transmission of pre-defined data





NRZ
non return to zero

Manchester
redundant transmission

1st half bit	2nd half bit	evaluation by receiver
0	0	detected failure
0	1	data bit = '0'
1	0	data bit = '1'
1	1	detected failure

Simple receiver / Manchester decoder
with over-sampling factor 2

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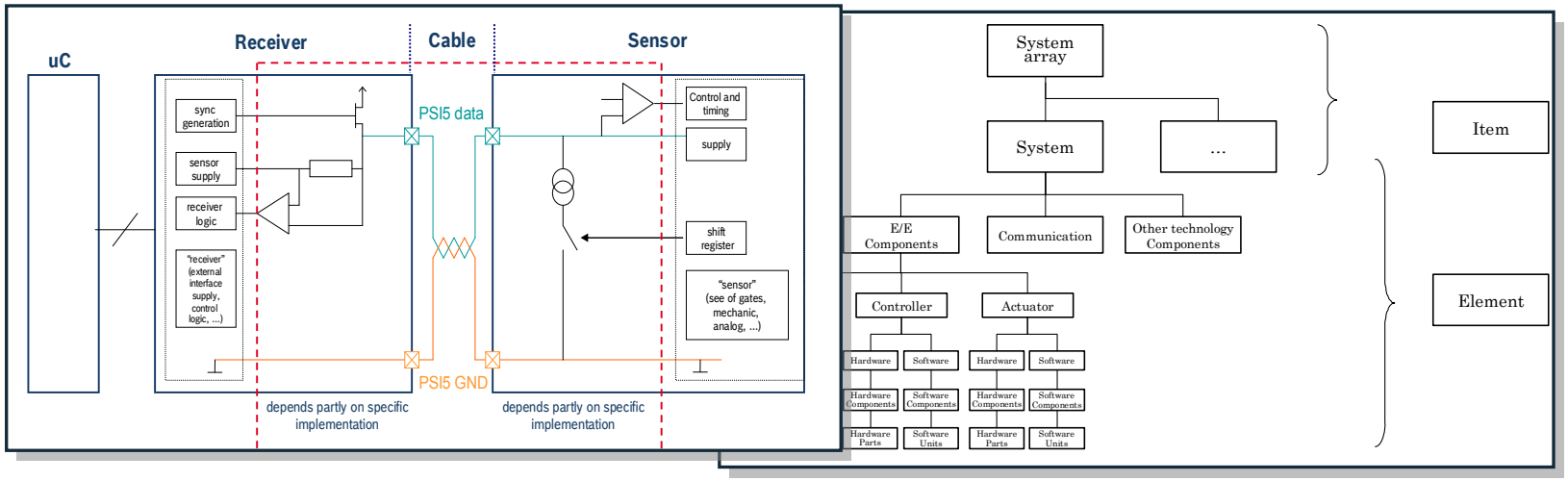
ISO26262 Requirements Applied to the PSI5 Interface

- PSI5 is an element of the system (component)
- Scope of discussion is the interface specification <u>without specific hardware implementation</u>



- Design measures to **avoid systematic failures** are one important requirement given by the ISO26262
- For random failures the **probability of undetected bit errors** is the important parameter as input for safety analyses

Source: ISO26262, BL18 FDIS

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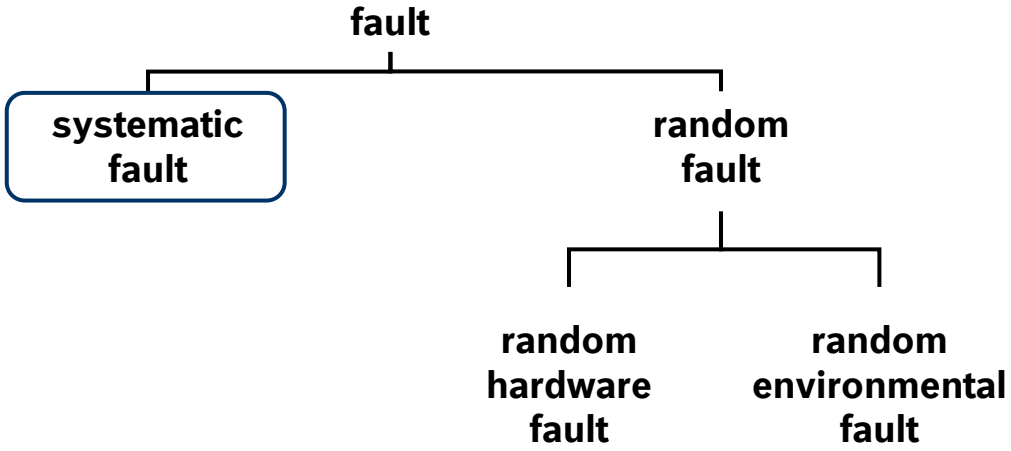
ISO26262 Fault Model and Failure Modes



A **systematic fault** is a fault "whose **failure is manifested in a deterministic way** that can only be prevented by applying process or design measures"

➔ Design and safety measures of PSI5 interface

Source: ISO26262, BL18 FDIS

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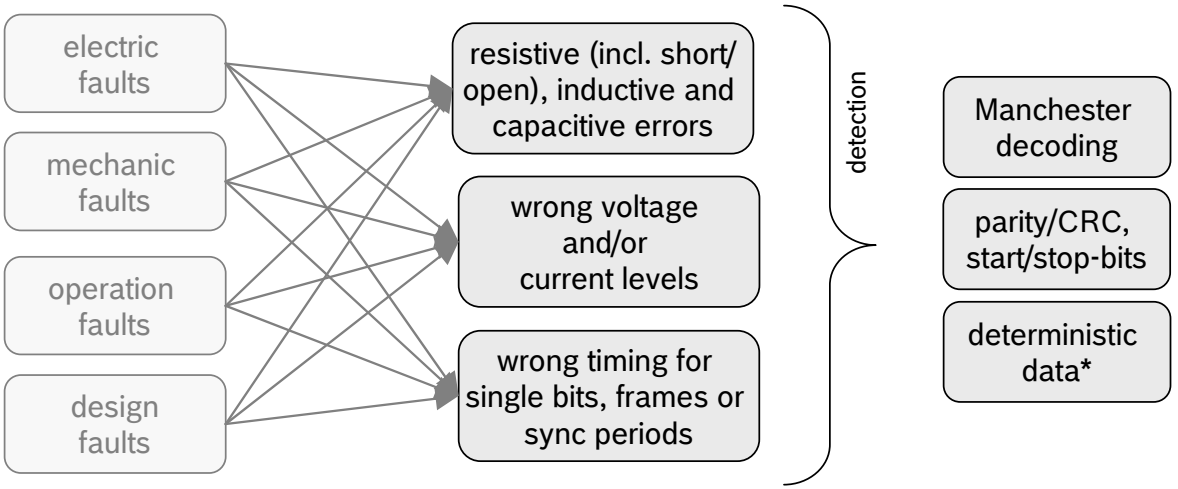
Faults, their Impact and their Detection

- PSI5 working group “Functional Safety” listed all systematic error modes and investigated effects and possible measures
- All systematic fault types given by the ISO26262 have additionally been considered (ISO2626-Part V – App. D – Hardware faults and Part VI-App D – “Exchange of Information”)



➔ Systematic failures can be safely detected by means of PSI5 specification on system level

**) Within the design of a PSI5 interconnection, it is predefined which data must be available (deterministic), missing data should be handled on system level.*

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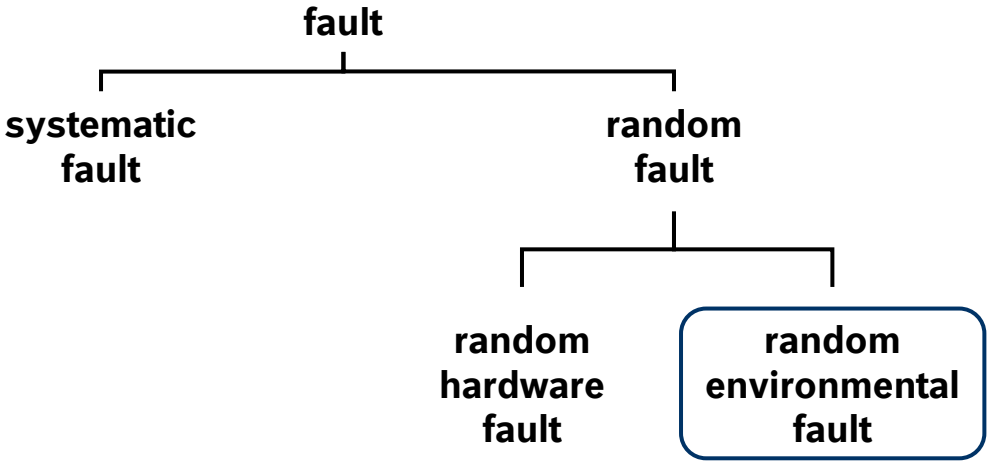

A **systematic fault** is a fault "whose **failure is manifested in a deterministic way** that can only be prevented by applying process or design measures"

➔ Design and safety measures of PSI5 interface

A **random fault** "can occur **unpredictably** during the lifetime of a hardware element and [...] **follows a probability distribution**"

➔ **Random hardware faults** (ASIC defect, defect of sensor or transceiver, ...) Implementation specific consideration necessary

➔ For PSI5 interface relevant: **not HW related but environmentally induced faults** (e.g. EMI induced bit errors)

Source: ISO26262, BL18 FDIS

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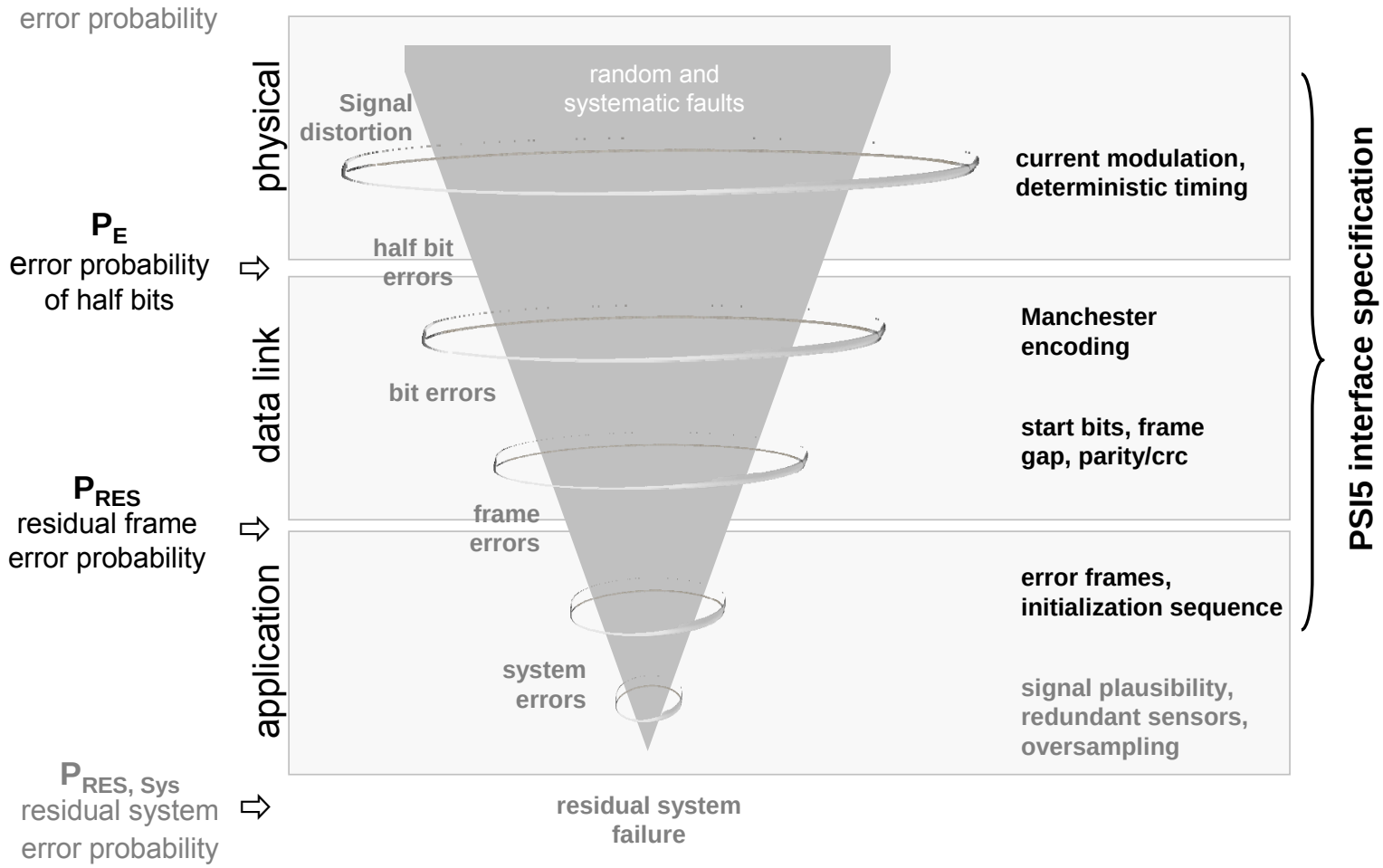
PSI5 Safety Concept



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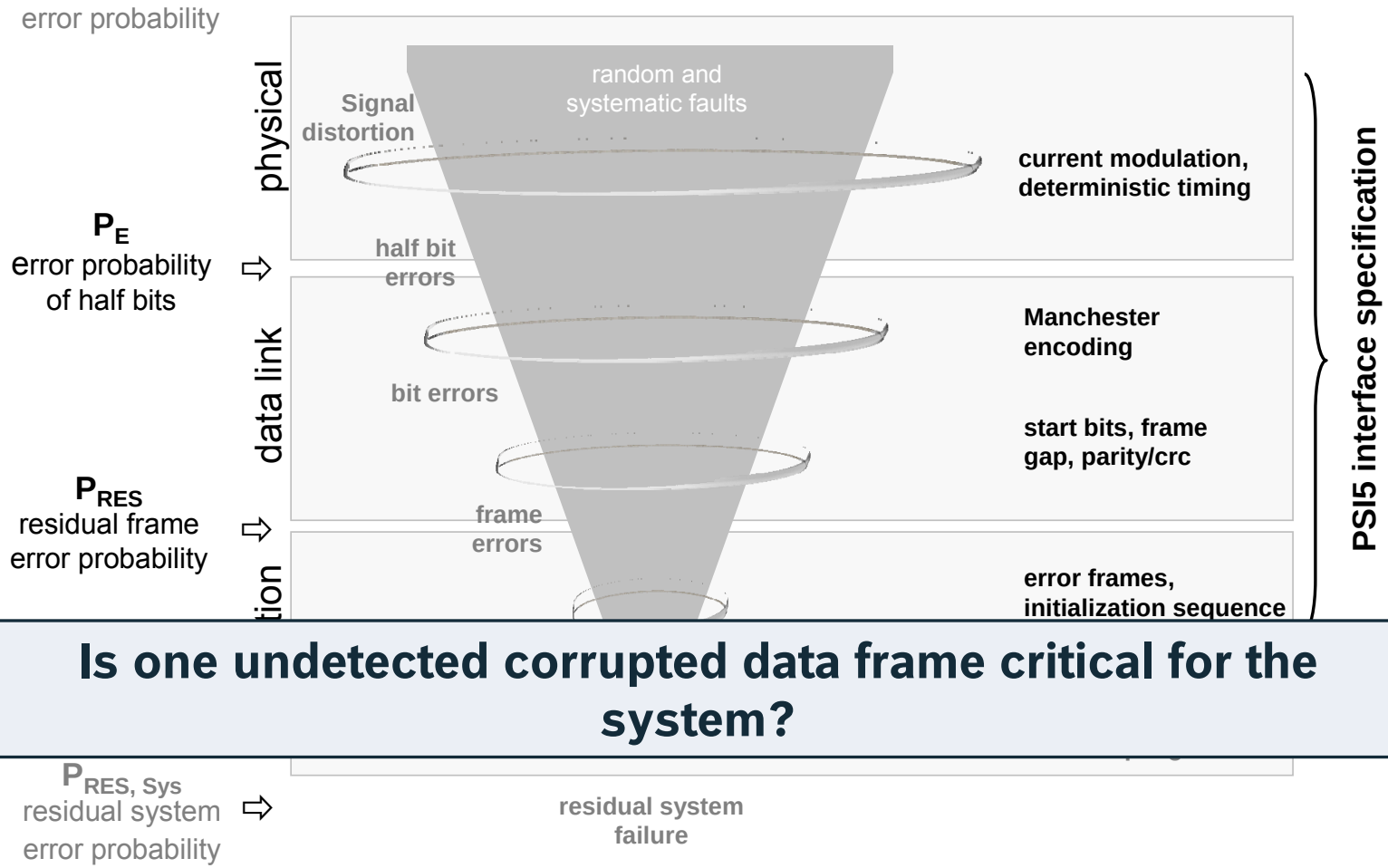
PSI5 Safety Concept



Is one undetected corrupted data frame critical for the system?

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Aspects of Functional Safety in System Context

P_{RES}: Residual error probability for one undetected corrupted data word
⇨ System goal? What is critical on system level?

Final judgement on „safety goals“ can only be done on system level:

- Residual failures regarding the LSBs might not be significant
- Are there plausibility checks with other sensor signals?
- How many subsequent data words cause a system failure
- By filtering methods single „wrong data“ can be suppressed
- Oversampling enables more intelligent data detection methods than assumed
- High probability of failure detection during start-up phase

⇨ **Further improvement of data reliability on system level**

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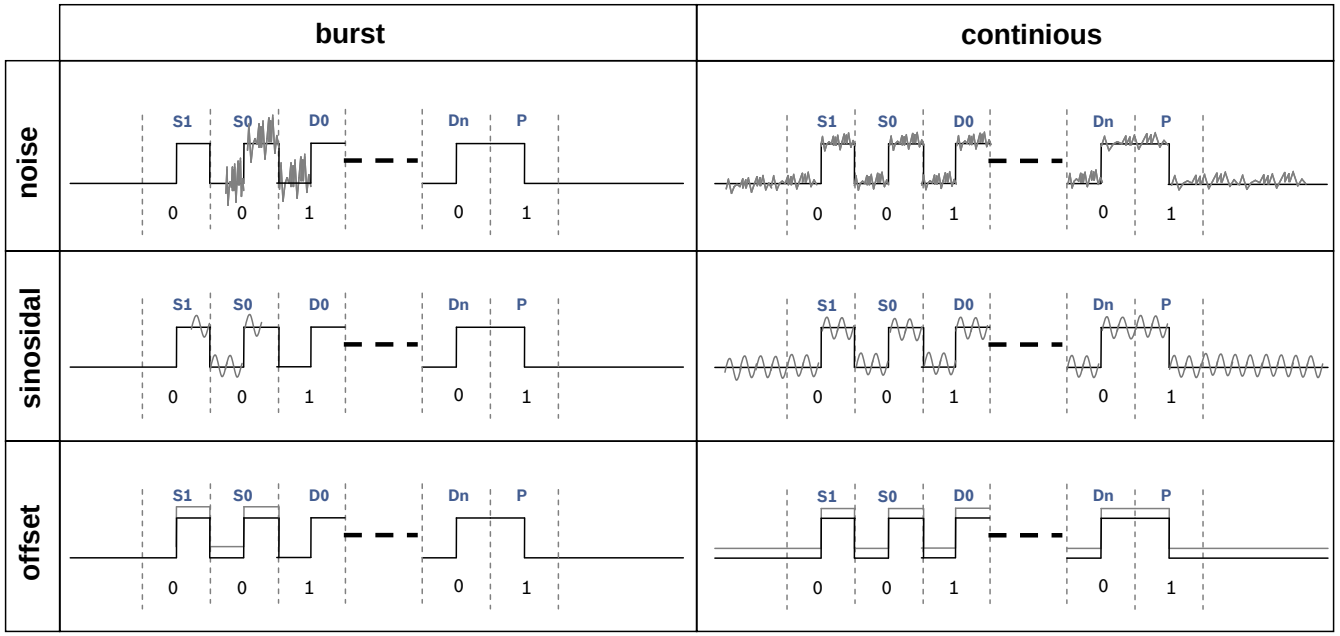
Random Environmental Failures – Physical Error Models



- All offset errors are detected by the Manchester encoding
- Models for Gaussian noise (continuous, burst) will be shown
- A model for sinusoidal disturbances (e.g. radio frequencies) will be shown

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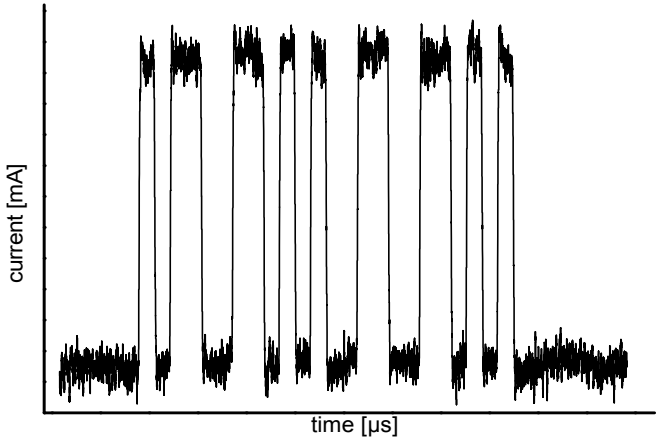
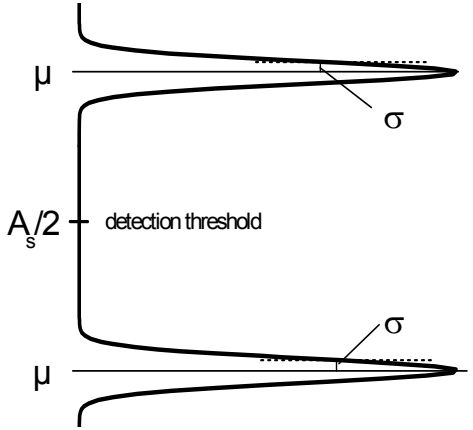
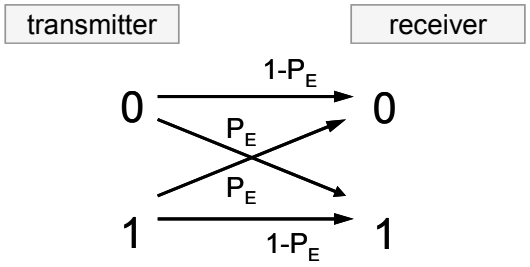
Noise Model – Additive White Gaussian Noise (AWGN)





binary symmetric channel (BSC)

as common channel model in communication theory



- ⇨ symmetric: P(1→0) = P(0→1)
- ⇨ memory less
- ⇨ "continuous": applicable for each half bit of PSI5 transmission

halfbit error probability P_E

$$P_E = \frac{1}{2} \cdot erfc\left(\frac{u}{\sqrt{2}}\right) = \frac{1}{2} \cdot erfc\left(\frac{\sqrt{SNR}}{2}\right)$$

with P_E : *probability of halfbit errors*

$$\text{signal to noise ratio} : SNR = \frac{A_S^2}{2\sigma_N^2}$$

A_S = *signal amplitude*; σ = *noise amplitude*

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Residual Error Rate with Additive White Gaussian Noise

Parity:

$$P_{Res} = \sum_{i=4,8,12,\ldots}^{n-4} \left(\binom{\frac{n}{2}-2}{\frac{i}{2}} \cdot P_E^i (1-P_E)^{n-i} \right)$$

CRC:

$$P_{Res} = \sum_{i=4,6,8,\ldots}^{n-4} \left(\binom{\frac{n}{2}-2}{\frac{i}{2}} \cdot P_E^i (1-P_E)^{n-i} \cdot CRC\left(\frac{i}{2}\right) \right)$$

P_E : probability of halfbit errors

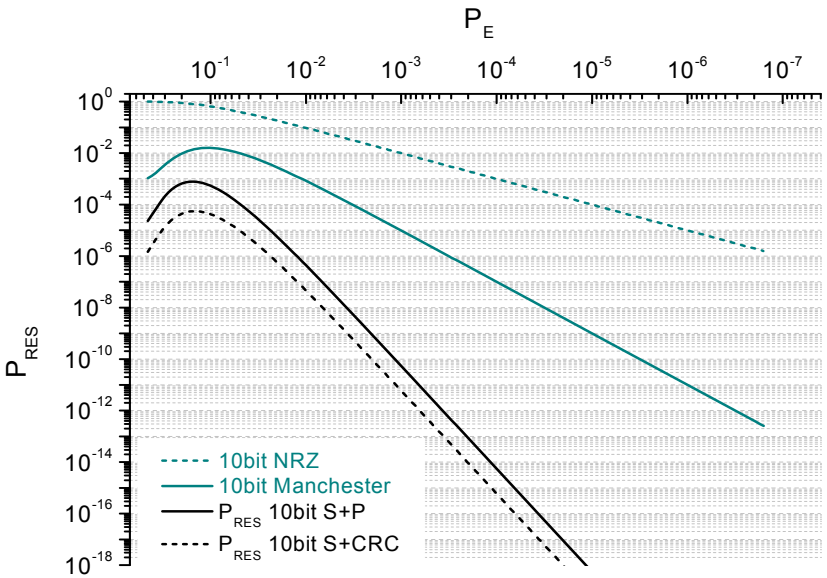
P_{Res} : Residual error probability

(= probability of undetected erroneous frames)

n : number of halfbits within one transmitted data frame

i : number of erroneous halfbits within one transmitted data frame

$CRC(x)$: percentage of " x" bit errors detected by CRC



Coverage by Manchester encoding, two fixed start bits and parity/CRC check

- Manchester decoder detects significant amount of errors
- Manchester + Start bits are important factor for very high bit error probabilities
- Parity and CRC have comparable P_{res} (both have Hamming distance of 2)

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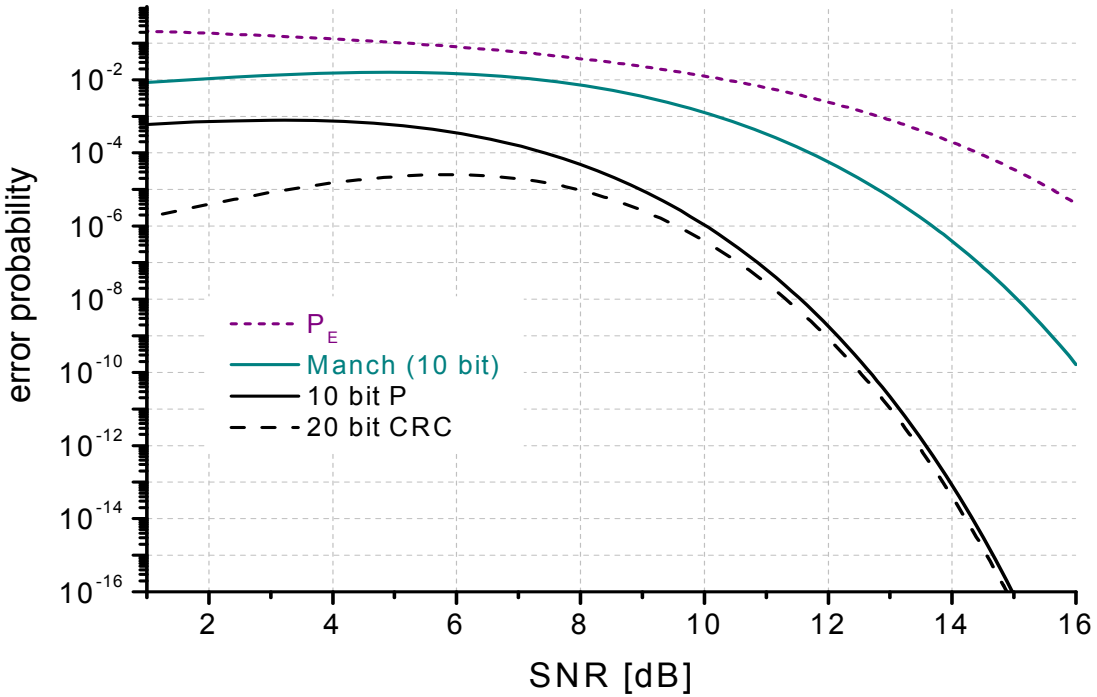
Residual Error Rate with Additive White Gaussian Noise

Replacing P_E by a function of the signal to noise ratio (SNR)



$$P_E = \frac{1}{2} \cdot erfc\left(\frac{u}{\sqrt{2}}\right) = Q\left(\frac{\sqrt{SNR}}{2}\right)$$

➔ Residual error probability <10-14 for SNR >14dB

➔ Comparable results for 10bit parity and 20bit CRC frames for SNR > 8dB

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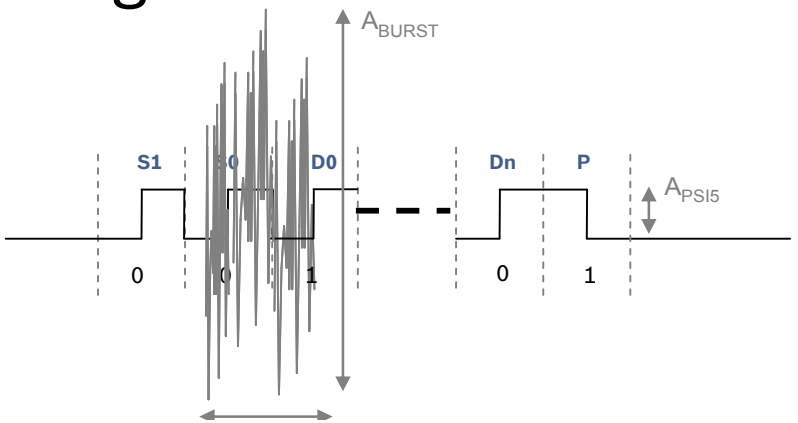
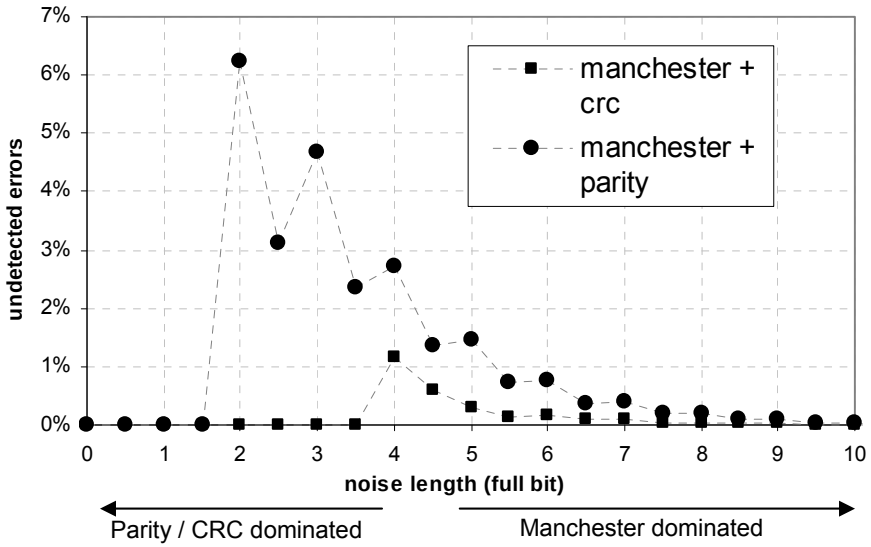
High Power Gaussian Noise Burst





Model

- Gaussian noise with maximum power (A_{BURST} >> A_{PSI5})
- Free parameter: length of burst

Result

- **“Short” bursts** (<4 / <8 halfbits) are **securely detected** by parity and CRC respectively
- Long burst are detected by Manchester decoding

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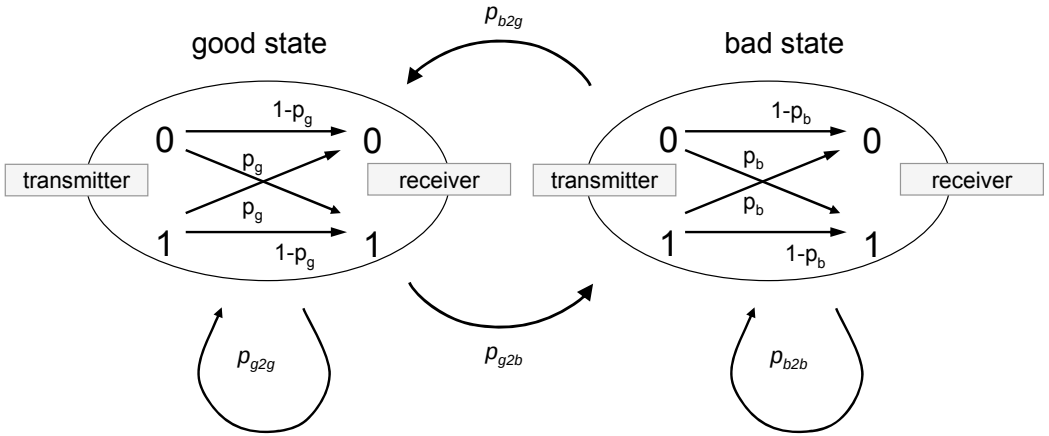
Alternative Modeling of Noise Burst Conditions

the two state binary symmetric channel (two state BSC, 1st order Markov Chain) describes a channel where transmission is interfered by **error bursts**



⇨ two states “BAD” and “GOOD” with different error probabilities

With assumption $p_g << p_b$

$$P_{Res} = \frac{p_{b2g}}{p_{g2b}} \sum_{i=4,8,12,\ldots}^{n-4} \left(\binom{\frac{n}{2}-2}{\frac{i}{2}} \right) \cdot P_E^i \left(1-P_E\right)^{n-i}$$

⇨ probability of bad state transition reduces residual frame error rate

Applied for two further burst models

- Burst „within“ a PSI5 frame *(next slides)*
- Burst for a sequence of complete frames →

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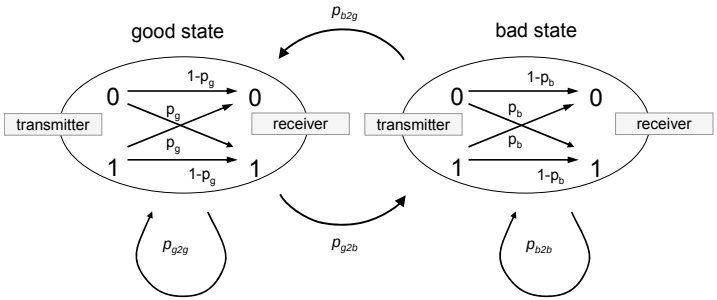
Two State BSC Noise Burst within a PSI5 Frame

Assumptions:

- State transition between two half bits
- Bad state can be entered maximum once per Frame (no multi bursts within one frame (p_{g2b}<<1)
- Practically no disturbance in good state (p_g << 1)
- Parity: detection of all odd errors
- CRC: hamming distance of 2 and detection of burst up to length of 3 used



Detection principles of PSI5 ➔

PAR: not relevant
CRC: burst <3bits

PAR: Odd errors
CRC: Hamming distance=2

Startbits and Manchester

Parity:
$$p_{res} = \sum_{n=1}^{N} (1-p_{g2b})^{n-1} p_{g2b} \sum_{i=1}^{N-n+1} (1-p_{b2g})^{i-1} p_{b2g} (1-p_{g2b})^{N+1-i-n} \sum_{\substack{k=4,8,12,... \\ k\le i}}^{i} (1-p_b)^{i-k} p_b^{\,k} \cdot \binom{\lfloor i/2 \rfloor}{k/2-s}$$

CRC:
$$p_{res} = \sum_{n=1}^{N} (1-p_{g2b})^{n-1} p_{g2b} \sum_{i=8}^{N-n+1} (1-p_{b2g})^{i-1} p_{b2g} (1-p_{g2b})^{N+1-i-n} \sum_{\substack{k=4,6,8,... \\ k\le i}}^{i} (1-p_b)^{i-k} p_b^{\,k} \cdot \binom{\lfloor i/2 \rfloor}{k/2-s}$$

with $\begin{cases} s=0 & \text{if } n>3 \\ s=2-\lfloor n/2 \rfloor & \text{else} \end{cases}$

Probability of states and bits ➔

- $(1-p_{g2b})^{n-1} p_{g2b}$: Probability to enter bad state (geom. distr.)
- $(1-p_{b2g})^{i-1} p_{b2g}$: Probability of bad state duration (geom. distr.)
- $(1-p_{g2b})^{N+1-i-n}$: Remaining bits within good state
- $(1-p_b)^{i-k} p_b^{\,k}$: Probability of erroneous half bits in bad state (geom. distr.)

Legend:
N: length of PSI5 frame
n: first halfbit of bad state
i: length of bad state
k: number of erroneous bits within bad state

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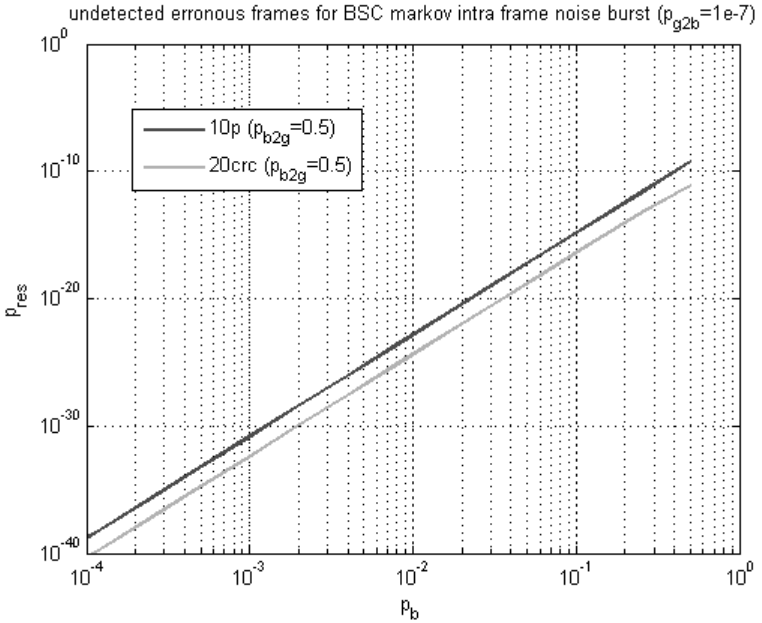
Two State BSC Noise Burst within a PSI5 Frame



Parameterization

p_{g2b} = 1e-7 } "short" burst with
p_{b2g} = 0.5 } "medium" probability

Example result

- CRC is slightly better than parity
- Very low failure rates expected (i.e. p_b<0.1 ⇨ P_{RES}<10^{-15})

Discussion of model assumptions

- Geometric distribution for bad state (event driven) and erroneous half-bits (random) plausible
- Geometric distribution for bad state length „assumed" (length given by effect duration?)

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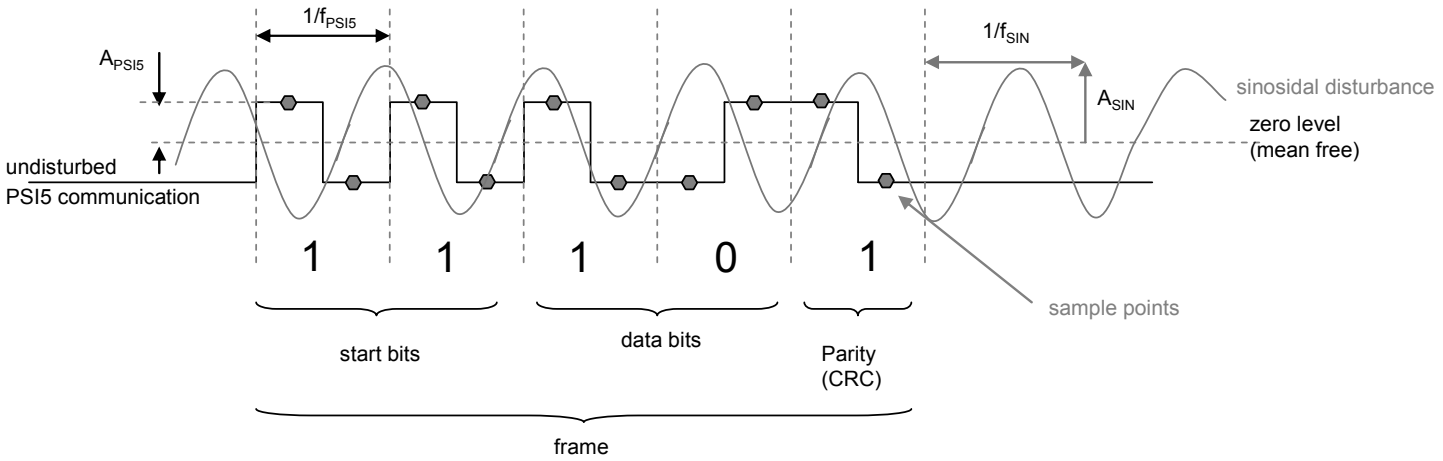
Sinusoidal Distortion Model



➔ Model is not „memory-less“, distortion of half-bits depend on frequency and phase

Assumptions of model:

- Constant disturbance amplitude, frequency and phase
- Offset free disturbance
- Simple two point sample model

Calculation of undetected errors in dependence of

- Amplitude *A* and frequency *f*
- Averaging over all phases and data words

} $P_{RES}(A,f)$

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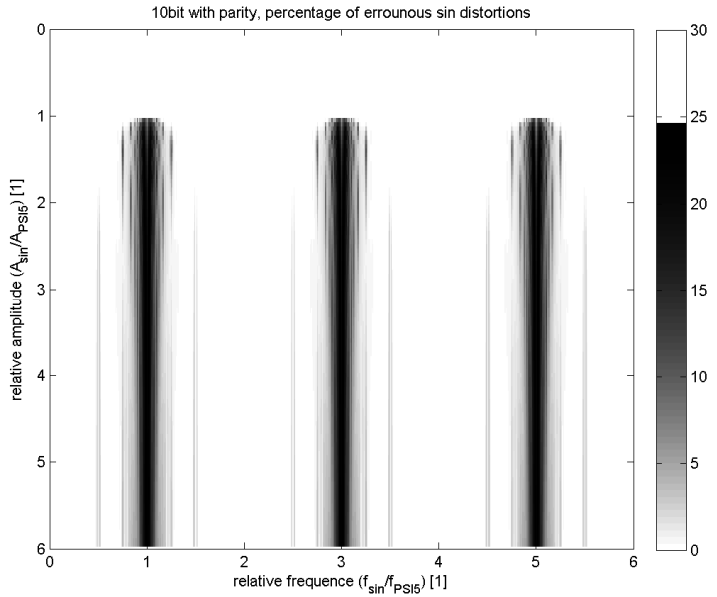
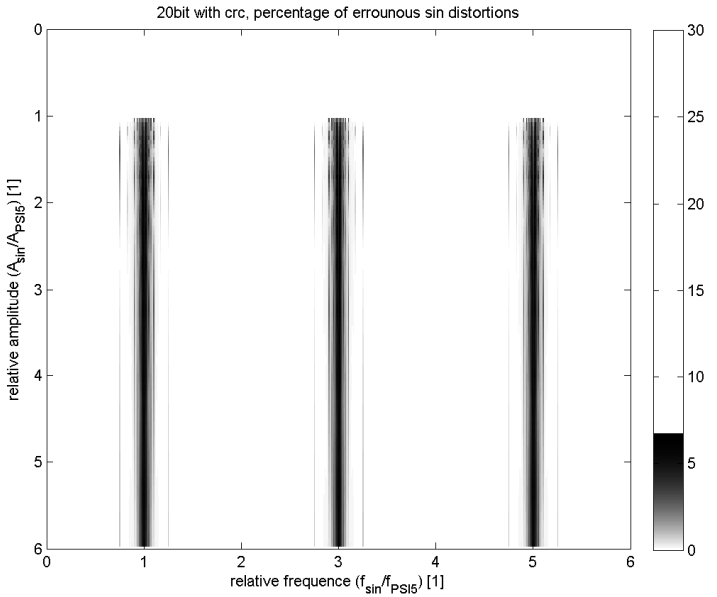
Sinusoidal Distortion Model - Result





- No errors for sinusoidal distortion smaller than A_{PSI5} (e.g. 13/2mA or 26/2mA)
- Most ranges are covered by Manchester decoding
- Odd multiple of PSI5 frequency are more vulnerable than other areas

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Conclusion Error Models

- ⇨ Offset distortion uncritical for PSI5 interface (Manchester)
- ⇨ Different error models with distinct modeling properties presented (Noise, Bursts, Sinusoidal)
- ⇨ Protection mechanism of PSI5 interface within error models described

- ⇨ Models can be used during system design to evaluate systems
- ⇨ Parameterization depends on implementation and real life effects (see next section!)

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Content

- Motivation: The PSI5 Interface and the ISO26262
- Systematic Failures
- Random Failures
  - Bit Error Models for Data Transmission
  - **Measurements of Transmission**
  - Application notes
- Comparison with other Protocols
- Conclusion

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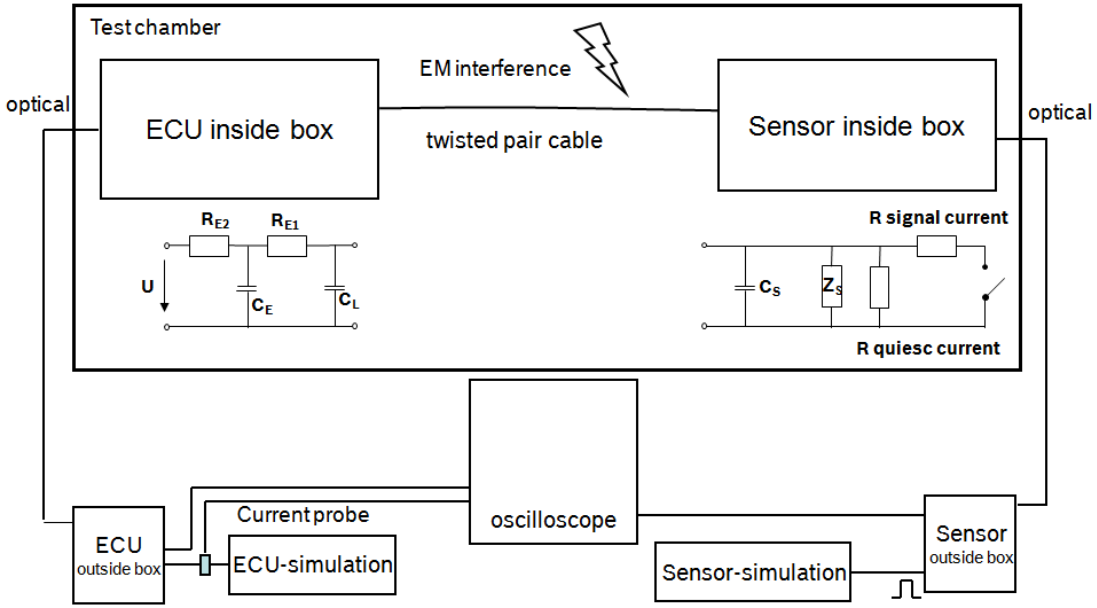
Measurement Setup and Overview



Scope

- BCI, antenna, transients
- in Compliance with:
  - ISO 11452-2, -4,
  - ISO 7637-3,
  - VDA-AK-LV 27 & 29

⇨ Result: for all standard tests, no transmission faults were seen

⇨ Measureable impacts only found after exceeding the standard automotive test ranges, or in cases of differential coupling on the cable (contrary to implementation)

*) Test parameter were chosen in compliance with the named ISO, or VDA standards, respectively. In some cases interference amplitudes were applied with significantly higher values than defined in the aforementioned documents - but still without measureable impact.

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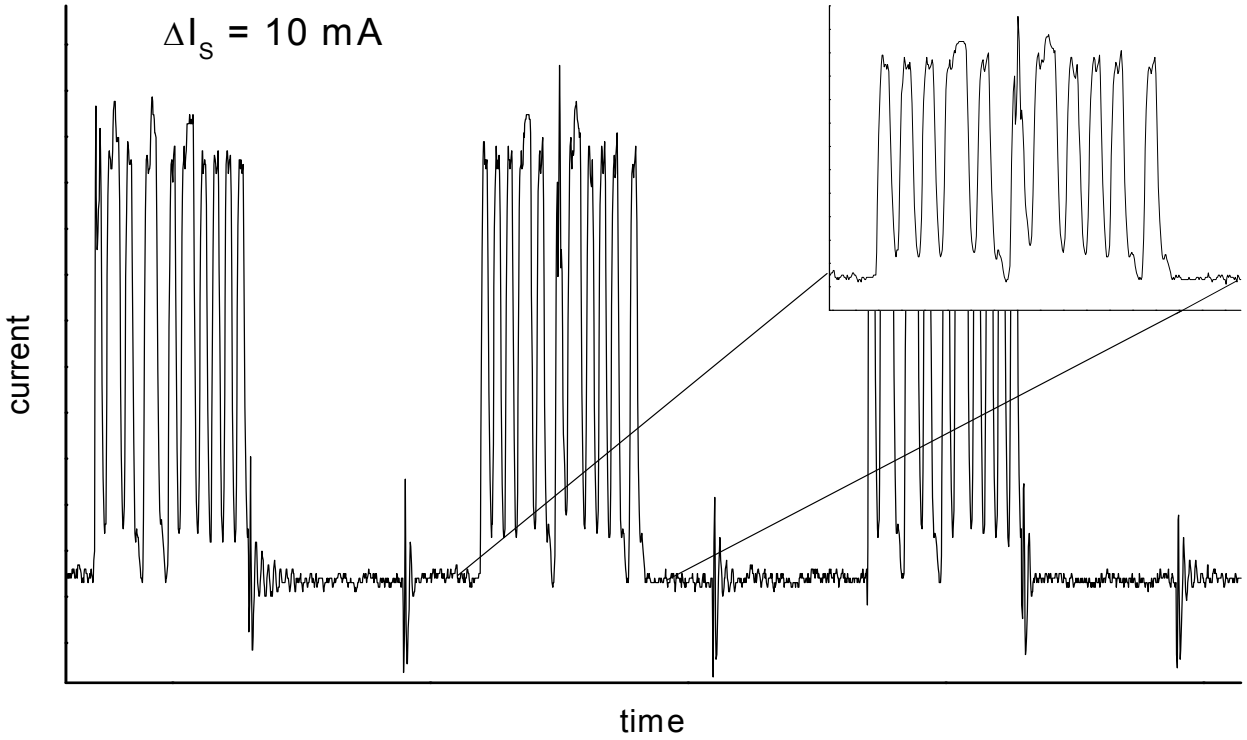
Transients Example

Example: ISO pulse (76373, pulse 3a,b, ±750V)



⇨ Duration of distortion << t_{bit} **(detection by Manchester or CRC/Parity)**

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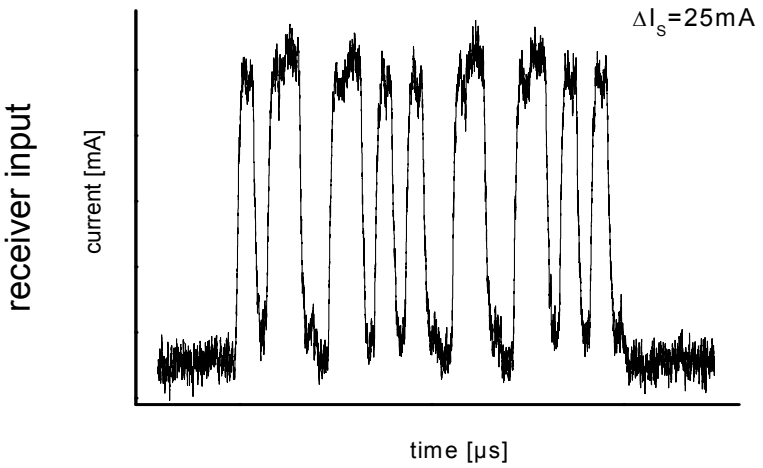
High Frequency Distortions – Example: BCI



- No influence by high frequency inductive coupling found
- The noise upon signal level is attributed to transmitter noise and measurement artifacts, not to “environmental” noise-sources
- However: when used as input for AWGN calculations the following error probabilities P_{RES} were derived:

$for\ \Delta I_S = 25mA:$	$for\ \Delta I_S = 12mA:$
$SNR = 25dB$	$SNR = 15.7dB$
$P_{RES} \rightarrow 0$	$P_{RES} = 1.8 \cdot 10^{-19}$

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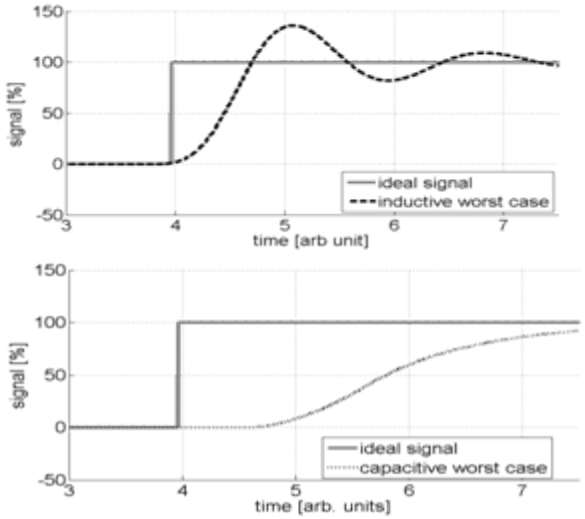
Excerpt: Influence of Bus Implementation on PSI5 signal

- For standard signal levels (ΔI_S=22…30mA) typical noise distortions (Gaussian type, as considered) are uncritical
- Margin can be used to compensate implementation dependent effects:
  - ripple on supply voltage (causes ripple on current signal)
  - tolerances related to the detection threshold
  - coupling between different PSI5 channels
  - signal over- and undershoots



"Resonant Worst Case"

- Long wires = High inductance
- Current modulation leads to current oscillations & overshoots

"Capacitive Worst Case"

- High capacitive bus load
- Limitation of slope steepness

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ISO26262 Application Example

⇨ Absolute metrics of ISO26262 (Probabilistic Metric for random Hardware Failures)
- Two start, one stop/gap bit, 10 data bits, one parity bit
- PSI5: ΔI = $26mA_{nom}$ / $22mA_{min}$, measured noise <$1mA_{rms}$
- Implementation specific adders : ΔI: -10mA noise: +$0.5mA_{rms}$
- 2kHz sampling rate, safety critical: 2 consecutive corrupted data frames

➔ Continuous Gauss model: <1e-20/h undetected critical failures

⇨ **Absolute metric of PSI5 seems to be not relevant for typical systems**

⇨ Relative metrics of ISO26262 (Single-Point Fault Metric [SPFM])

(estimates)	(bit) error rate	residual failure rate	SPFM
• PSI5:	~1e2/h*	~1e-20/h	99.999…%
• HW	~1e-8/h	~1e-9/h	90%
• System	~1e2/h	~1e-9/h	99.999..%.

➔ Calculated SPFM for a system with PSI5 would probably be >>99%

⇨ **Relative metrics are so good, that they would overlap other parts if used**

* with continuous Gaussian model, assumed PE ~10-5 and 2kHz sampling rate

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Summary Measurement Results and Application Notes

- ⇨ EMI robustness of the PSI5 interface was shown
- ⇨ No data failures detected due to robust physical layer
- ⇨ Residual error probabilities for measured PSI5 signals $P_{RES} << 10^{-19}$
- ⇨ Be careful when using the PSI5 failure rates for ISO26262 metric calculations

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Safety and Performance Comparison I/II

- ⇨ Comparison of different interface features*) with respect to
  - ⇨ their functional capabilities
  - ⇨ their impact on error probability (i.e. random and systematic)
  - ⇨ their error detection capabilities

- ⇨ Common automotive interfaces for systems with unidirectional data communication considered (PSI5, DSI, SENT, CAN, FLEXRAY)

- ⇨ Higher functionality implies higher safety needs; examples:
  - → Multi master systems (i.e. CAN)
    - → high risk of collision (data of several masters at the same time)
      - → counter measures as “bit read back” implemented
  - → Non time-deterministic data (i.e. Flexray optional data)
    - → high risk of missing data
      - → counter measures as “cycle count” implemented

*) *Aspects like Implementation costs or backward compatibility to former revisions not considerd*

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Safety and Performance Comparison II/II

PSI5		DSI		SENT		CAN		FLEXRAY		PREFERRED FEATURE UNDER SAFETY ASPECTS
deterministic (time slots)	+	deterministic	+	deterministic	+	non- deterministic	-	deterministic + non- deterministic	+	deterministic
single master	+	single master	+	single master	+	multiple master	0	multiple master	0	single master transmission
unidirectional (opt. bidir.)	0	unidirectional (opt. bidir.)	0	unidirectional	+	bidirectional	0	bidirectional	0	unidirectional
125kHz/189kHz	+	typ: 250-300kHz	+	variable	+	125kHz -1MHz	+	2,5-10MHz	0	lower frequency
Manchester	+	TDCA: 16/27 encoding	+	PWM	-	NRZ	-	NRZ	-	redundant signal coding
parity / 3bit CRC	0	8bit CRC	+	4bit CRC	+	15bit CRC (but bit stuffing issue)	+	11bit + 24bit CRC	+	higher Hamming dist.
high current modulation	+	high current modulation	+	voltage modulation	-	voltage modulation (differential)	0	voltage modulation (differential)	0	robust modulation
fixed start/stop bits	+	n/a	0	n/a	0	multiple fixed bits	+	2 fixed bits per byte	+	fixed bits
initialization phase, free to use bits (i.e. counter)	+	optional: message counter	+	n/a	0	Bit read back, Bit stuffing, Acknowledgement, Error Frames	+	cycle count	+	additional protocol measures

Sources: PSI5 Technical Specification V2.0 (2011); DSI3 Bus Standard Rev 1.00 (2011); SENT—Single Edge Nibble Transmission for Automotive Applications – SAE J2716 FEB2008; CAN Specification 2.0 (1991); FlexRay Communications System – Protocol Specification V 2.1 (2005)

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Comparing PSI5 to Other Interfaces

⇨ Comparison between interfaces needs to consider performance and safety features (higher performance needs distinct safety features)

⇨ The safety concept of the PSI5 is “State of the Art” considering its functional capabilities (i.e. no need of bit read back, frame counter, …)

⇨ For systems which need advanced functionality (i.e. multi node bidirectional communication, ensured availability, ….) protocols like CAN, Flexray or others, which therefore feature additional safety mechanisms, should be used

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Conclusion

- ⇨ Systematic failure prevention was one main focus of PSI5 development
- ⇨ The PSI5 interface shows very high data reliability:
  → residual error probability $<10^{-14}$ for SNR >14dB
- ⇨ Parity check sufficient for small data words, CRC recommended for large frames
  → 10bit parity and 20bit CRC frames have comparable P_{RES} for SNR > 8dB
- ⇨ PSI5 interface is comparable in safety to other automotive interfaces and a state of the art sensor interface
- ⇨ Presented methods and argumentations support conformity considerations regarding ISO26262 for systems rated up to ASIL D.

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CONSIDERATIONS ON FUNCTIONAL SAFETY OF THE PSI5 INTERFACE IN THE SCOPE OF THE ISO26262

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Abstract

With PSI5 (peripheral sensor interface) a standard for data transmission in automotive safety applications has been established. Originally designed for airbag applications, the new specification 2.0 covers additional fields of application like engine management and vehicle dynamics. In this paper several aspects of PSI5 related to the road vehicles functional safety standard (ISO26262) are discussed.

The safety mechanisms of the PSI5 interface are described and its particular ability to handle systematic errors is shown. Different error models are discussed and compared to measurements. Reference is given to other standard interfaces used in automotive E/E networks.

Results and conclusions support conformity considerations regarding ISO26262 for systems rated up to ASIL D.

Keywords: PSI5, Communication Protocol, Manchester, bit error probability, ISO26262, Functional Safety

1 Introduction

The PSI5 consortium was founded in 2004. The original scope was the development of a robust interface between sensors and electric control units (ECU) for airbag applications.
Dealing with safety electronics – wrong data may cause a non-deployment of an airbag during a crash, or an airbag deployment without crash – a high data reliability was the main focus within the PSI5 consortium. Therefore, many existing interface protocols, like PAS3/4, PEGASUS, MERAS, RSU or MRSA have been considered[OHL], taking the best of each. One important aspect for the design of PSI5 was that failure prevention is better than failure detection.

Since then, PSI5 has been established world-wide for airbag applications. Now, the PSI5 specification has been extended for a wider field of applications. The specification version 2.0 contains extensions for engine management and dynamic control applications [PSI5], [REIM], [BOCK].

In 2010 the working group “functional safety” was founded within the PSI5 consortium. Main target was to give guidance for conformity considerations regarding the ISO26262 standard of functional safety for road vehicles [ISO], also with respect to the new applications that require a partly widened parameter field.

1.1 ISO26262

The ISO26262 standard is a vehicle to master the permanently increasing safety requirements within the automotive area. With the final release of the ISO standard, published in 2011, the safety requirements and methodology described within are universally claimed not only to system manufacturers but also to each part of the system development process, i.e. to each (sub-) supplier in the whole production chain.
This paper intends to give support for those who develop automotive systems or components that use the PSI5 interface for communication between peripheral sensors/actuators and the control unit. Its goal is to give basic technical considerations and conclusions that can be used for application specific safety analyses.

An evidence of compliance with or violation of safety goals cannot be given from this reflection level, neither a common statement of residual random hardware failure rates of the PSI5 interface because detailed system requirements and knowledge about system architecture are necessary for validation.

2 PSI5 Interface

This chapter describes the main aspects of PSI5, its measures to provide a robust interface and details about its protection mechanisms.

2.1 Concept

PSI5 connects sensors or actuators to a control unit on the basis of a 2-wire cable. The cable serves both for power supply of the sensors or actuators and for data communication. For that purpose the ECU transmits so-called “sync-pulses” by modulation of the voltage. The sensor or actuator responds within predefined time slots with current-modulated data. A schematic of the interface is depicted in Figure 1. Accordingly, PSI5 allows a cost-efficient implementation.

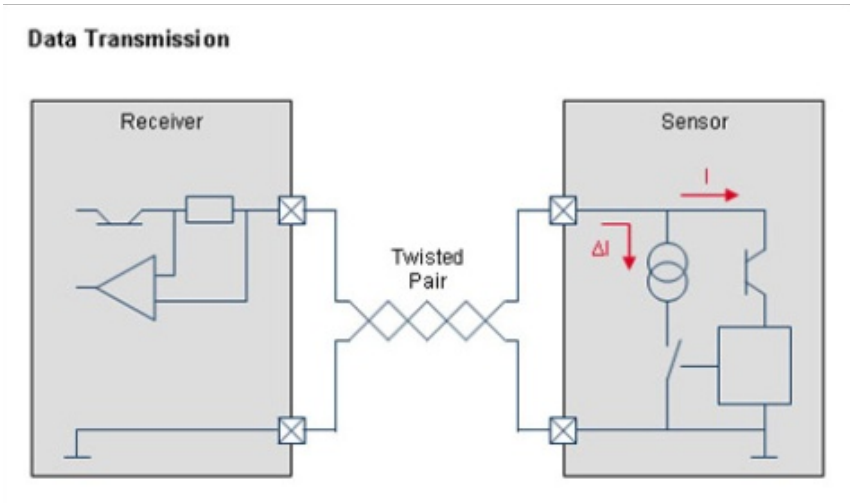


Figure 1 Implementation scheme of the PSI5 interface

Optionally, data can be transmitted also asynchronously: Data words are sent in specified intervals. Sync pulses are not required in that case.

For bidirectional communication specific sync pulse patterns are used to transmit commands to the sensors/actuators, e.g. for sensor addressing in case of a daisy chain bus, the configuration of bus devices or the activation of actuators.

Synchronous transmission enables time-division multiple-access, i.e. the data words of various sensors or actuators are assigned to different time slots. This way several sensors (actuators) can share one cable. In principle, PSI5 supports parallel and daisy chain bus, the former in star and parallel bus topologies, the latter in parallel mode.

2.2 Measures for data reliability

As mentioned above, data reliability is the key requirement of PSI5. On the physical layer this is realized by a simple concept; high signal current levels with a maximum level of 30mA provide a large signal to noise ratio (SNR) and hence, good electromagnetic compatibility. Besides, the twisted pair cable compensates for distortions within a homogenous field.

On the data link layer there are several further measures to guarantee a high transmission performance: The signal data is Manchester-encoded, i.e. most of all potential signal distortion can be detected by missing or implausible signal transitions. As shown in Figure 2, compared to a non return to zero (NRZ) signal, Manchester encoding corresponds to a fully redundant transmission: Data information is given by transitions instead of signal levels.

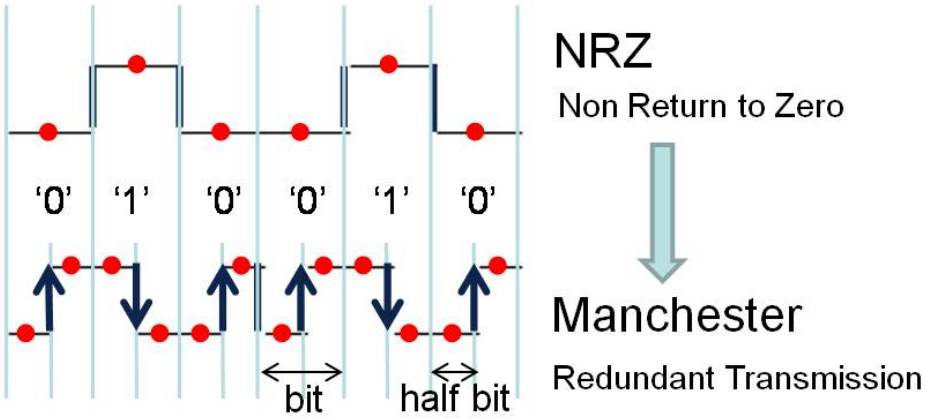


Figure 2 Redundant Data Transmission of Manchester decoded data compared to a NRZ signal

Table 1 shows a Manchester decoder scheme, assuming a simple receiver working with over-sampling factor 2. We see that only failures of 2 subsequent “half-bit” errors are critical with respect to the residual failure rate on bit level. We refer to this fact as “Manchester condition” in the following.

1st half bit	2nd half bit	evaluation by receiver
0	0	detected failure
0	1	data bit = '0'
1	0	data bit = '1'
1	1	detected failure

Table 1 Manchester decoder scheme

In addition, data words are protected by a parity bit or by cyclic redundancy check (CRC) bits. By means of start and stop bits (defined minimum gap between two frames) timing failures can be detected. Furthermore, failure detection can be enhanced by evaluating data during initialization phase.

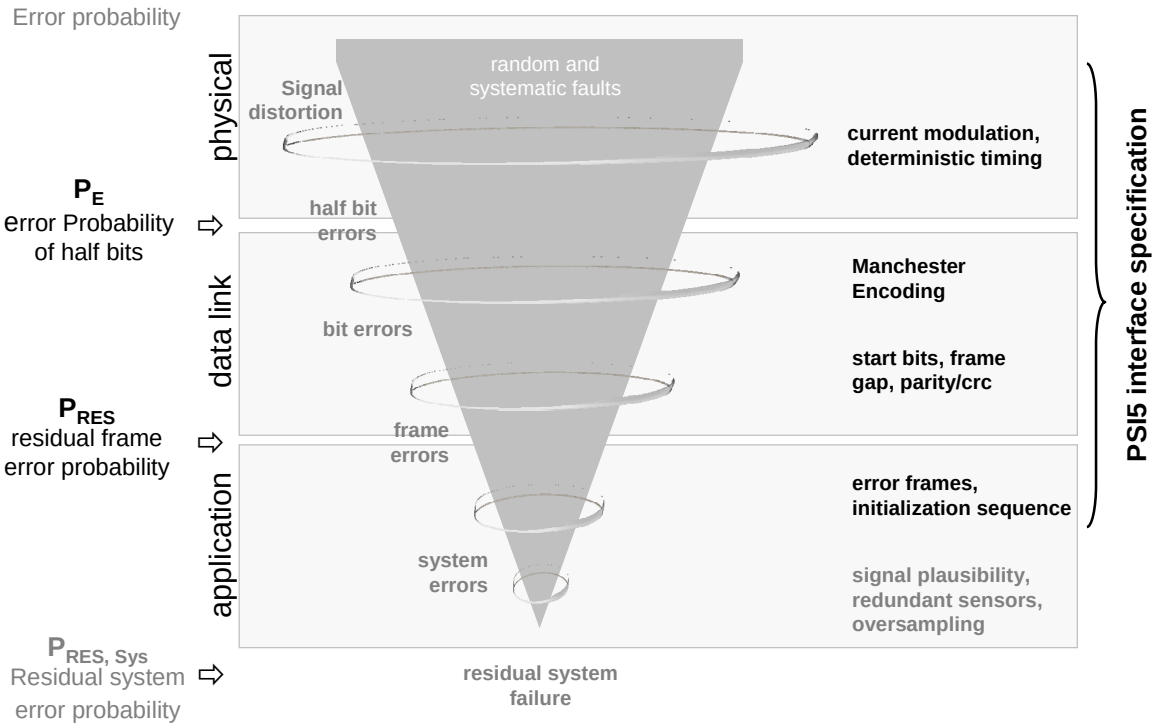


Figure 3 PSI5 safety concept

Figure 3 shows the described methods for failure detection. Due to physical signal distortions “half bit” errors may occur, despite of current modulation and synchronous transmission. The according half bit error

probability is called P_E[1]. After the Manchester decoding full bit errors might remain undetected. Applying additional measures on data link layer the probability for residual frame errors – P_{RES} – is further reduced. Finally, there are even more means on system level for failure detection, resulting in the residual system error probability. Furthermore, residual failures regarding LSBs might not be significant, failure detection could be enhanced on the basis of plausibility checks with other sensor signals, one single frame error may not cause a system failure, single frame failures can be suppressed by filtering methods and higher oversampling enables smarter data detection methods than the ones assumed above.

This paper addresses the residual frame error probability; a final judgment on “safety goals” cannot be given here. It can only be done on a system level.

Summarizing this list, there is additional space for improvement of data reliability on a system level. Additionally, the mentioned methods also contribute significantly to the avoidance of systematic faults as will be discussed in more detail in chapter 3.

2.3 Parity and cyclic redundancy check (CRC) detection capabilities

The parity check has the power to detect all bit error patterns with an odd number of single bit errors. The PSI5 CRC can find 87.5% of all bit error patterns. The detection capability is almost equally distributed over all possible bit error counts. Both, CRC and Parity can detect all one bit errors (Hamming distance of two) and the case that all bits are flipped. Figure 4 shows, for all possible counts of bit errors, the percentage of undetected bit error patterns for parity and CRC check.

[1] Another term for half bit error probability, or rate is the frequently used symbol error probability/rate.

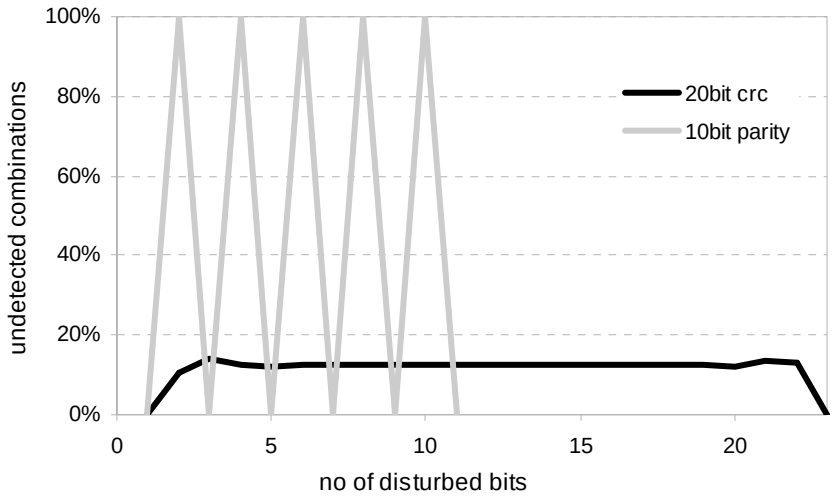


Figure 4 Single bit error detection capabilities of parity and CRC mechanisms

Additionally, the CRC can detect a high number of bit burst errors. A bit burst of the length n is an error where up to n consecutive bit errors are present. For the PSI5 CRC the following three properties are given [FRIE]:

- 100% of all bit burst up to n=3 are detected
- 75% of all bit burst up to n=4 are detected
- 87.5% of all bit burst of n>4 are detected

The properties of the parity and CRC checksum respectively will be used in later sections. The ISO conformity will be discussed in chapter 3.2. Other frame length and checksum combinations can be easily derived.

3 ISO26262 requirements to PSI5

As mentioned above, it is not the intention of this paper to make a statement concerning the safety classification of the PSI5 interface itself, since such a statement must be done for the whole system and requires detailed knowledge about its requirements and architecture. Thus, it is necessary to define certain prerequisites for the following discussion. The first and essential conclusion is that the PSI5 interface is an element of the system according to the ISO26262. Therefore systematic failures have to be considered and prevented. The failure rate of the interface is the important parameter for safety metric calculations.

The ISO26262 standard distinguishes between systematic and random faults. A systematic fault is a fault “whose failure is manifested in a deterministic way that can only be prevented by applying process or design measures” whereas a random hardware fault “can occur unpredictably during the lifetime

of a hardware element and […] follows a probability distribution”. The ISO26262 only knows random failures for hardware elements. However the PSI5 communication can not be considered as a hardware element, but might also be a source of errors in certain circumstances. Electromagnetic interference, for example, is also an unpredictable fault following a certain probability distribution over lifetime resulting from an external influence which is not related to damaged hardware. This kind of fault is classified as a random environmental fault since it is caused by a defined environmental circumstance in an unpredictable way. In contrast, a random hardware fault would be, for example, a damaged EMI protection capacitor. The classification of the different fault types is pictured in Figure 5.

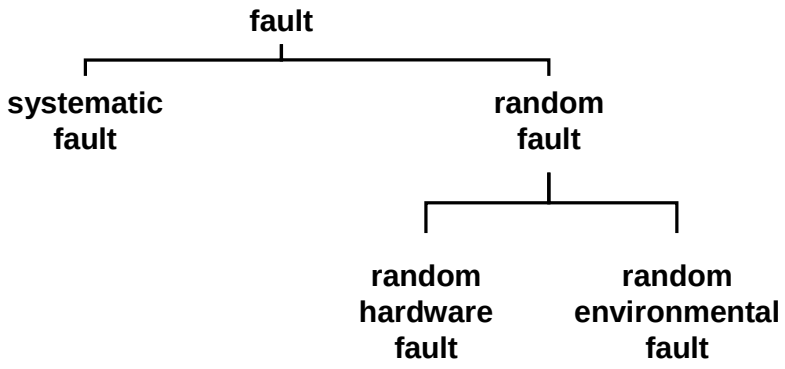


Figure 5 Classification of different fault types

Random hardware fault considerations cannot be the content of a generic discussion of an interface since they depend on the actual implementation of the PSI5 interface specification. However, a more detailed discussion of generic systematic failures is given in chapters 3.1 to 3.3 by aspects of the interface itself, considerations resulting from the ISO26262 and comparison to other interfaces. Random failures are described in chapter 3.4 and due to their important role for the interface safety, a thorough discussion of random environmental failure models, their parameterisation within automotive environments, and their application for actual systems is given in chapter 4 to 5.

3.1 Considerations on systematic faults of the PSI5 interface

Considered elements that can act as cause for systematic failures of the PSI5 interface are the twisted pair cable and parts of the receiver and the sensor that are directly linked to the interface as shown in Figure 6.

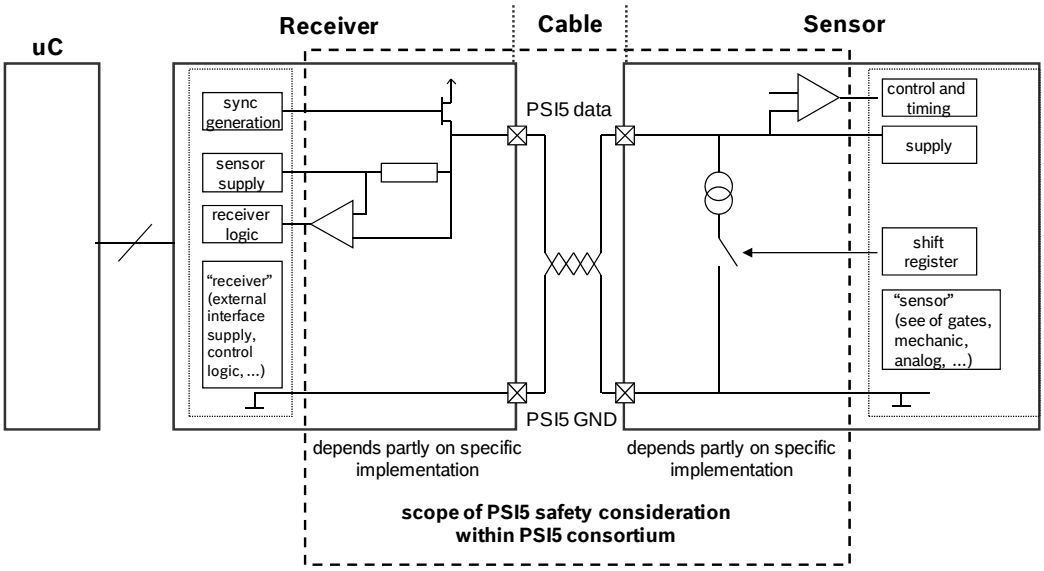


Figure 6 Scheme of the PSI5 interface and visualization of the considered scope

Consequential faults are shorts, open wires and drift of wire properties. Faults of the supply voltage level (too high/low) and the timing (to fast to slow) of the synchronisation pulse on receiver side, as well as quiescent and modulation current and their timing on the sensor side have also been considered. The main events are depicted in Figure 7, where on the left hand side the arbitrary faults leading to a systematic fault (middle) are shown. Failure detection mechanisms are depicted on the right hand side. A detailed analysis will be released on the PSI5 web page [PSI5web].

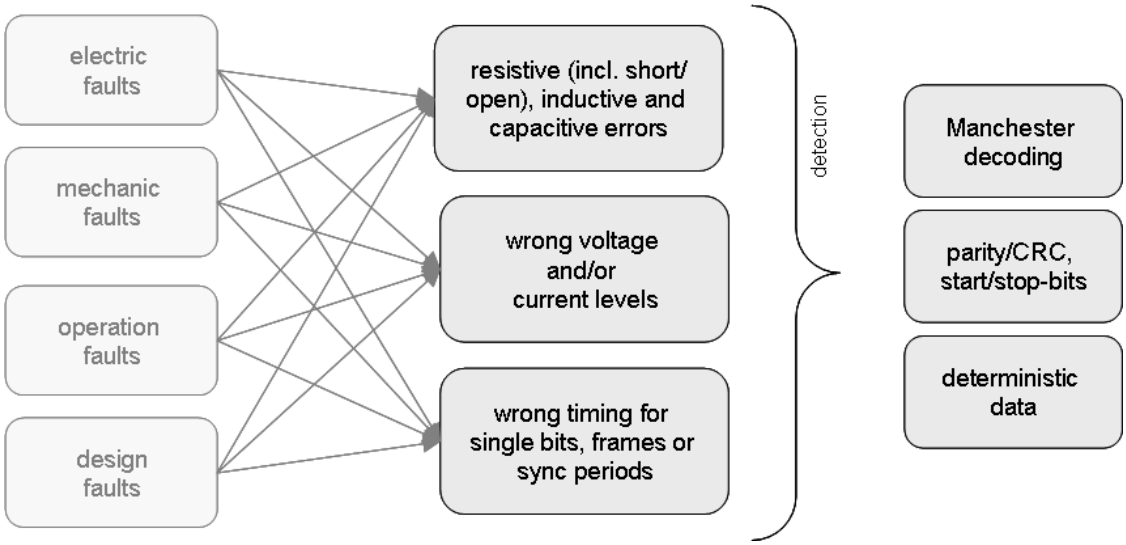


Figure 7 Cause and detection mechanisms of systematic faults for the PSI5 interface

As stated above, the faults can only be assessed on functional level and the detailed hardware fault analysis has to be done for the final implementation of the interface. However, the PSI5 interface specification has been analyzed for its ability to cope with several generic faults. With the following results:

- For synchronous operation modes all systematic faults will be detected if the receiver can detect a Manchester error and a missing frame (due to a deterministic data flow). The parity/CRC check is not even needed to detect these faults.
- For Bidirectional communication the additional CRC is needed to detect a missing or wrongly added / detected sync pulse.
- An unintended sensor restart due to a low voltage or short time supply interruption will lead again to sensor initialization. Initialisation data is marked specially and will thus not lead to a safety critical state. However, the temporary unavailability of the sensor signals should not affect the system.

3.2 Systematic fault considerations required by the ISO26262

The ISO26262 gives several hints on failure modes that should be analysed and even proposals on prevention mechanisms are given (see ISO26262, Part 5 Appendix D, and Part 6, Appendix D). All given hints have been analysed in the context of the PSI5 interface. Due to the simple and thus robust design specification of the PSI5 interface, it was found that all aspects are covered, if applicable. A complete listing is given on the PSI5 web pages [PSI5web].

One requirement of the ISO26262, which is often discussed, is the question of the Hamming distance that is needed for failsafe communication. For the Hamming distance of the PSI5 interface, not only the parity and CRC mechanism respectively, but also the Manchester encoding has to be considered, leading to an effective distance of 3. However, even a “Medium diagnostic coverage: Hamming distance of 3 or more” [ISO] does not necessarily suggest an insufficient interface. For systematic faults it was shown in section 3.1 that even a one Hamming distance would be sufficient to cover all systematic faults. For random faults the probability of a fault has significant influence on the system performance. For a, not yet invented, wireless airbag firing switch a hamming distance of 4 may not even be enough, while for on board serial communications within an engine control unit even unprotected data still is state of the art and sufficient to guarantee a safe system.

Another suggestion from the ISO26262 is the insertion of a frame counter. Even if the PSI5 interface provides the possibility to use such a counter, it is unnecessary in many cases and may be omitted in favour of a higher protocol payload. The PSI5 information is transmitted in a deterministic way, missing data can easily be detected by a reasonable receiver design. Switching information of two independent sensors within a PSI5 bus is impossible. Mixed signals due to broken hardware should be avoided by a robust hardware design.

3.3 Systematic faults in comparison with other automotive interfaces

To judge the safety performance of the PSI5 interface, it is compared with other interfaces used in safety related automotive E/E systems. The safety of an interface is not only given by its safety mechanisms. Also the performance capabilities have to be considered. A simple deterministic point-2-point connection does not need the same safety mechanism as a multi master non deterministic high speed interface. Also the physical properties and the environment in which an interface is used are important to evaluate the power of the safety mechanism. A wireless connection of four tire pressure sensors within a fleet of vehicles might be much more error prone than a local hard wired and shielded connection. In the following comparison mainly the scope of operation where PSI5 is used is considered. In operation areas that require higher functionality, which is provided by other protocols like CAN or Flexray, additional and more sophisticated safety measures might be needed. However, within a system where an unidirectional communication is needed, using an interface with a multi master functionality increases the complexity unnecessarily and should be avoided according to the ISO26262 [ISO26262 – part 5 table 2].

The features and functions outlined here are reduced to single master functionality and assessed against the background of specific implementation cases.

Each protocol has its specific advantages. The safety mechanisms are adjusted to the protocol specific needs. A message counter for example is important for non deterministic protocols with intermediate hubs where there is a realistic probability for faults that lead to a mixing up of signals. It is obvious that a simple discussion of the CRC order is not enough to judge the safety of a protocol. For modern designs of robust interfaces, a lot of effort is put on the physical layer which enables a design where (bit) errors are very unlikely to occur. The features of the protocols are adjusted precisely to the needs of the users enabling protocol specific safety measures. At this point it has to be emphasized that PSI5 is not

designed for multi master application. Hence, safety requirements only have to address single master aspects.

Table 2 shows an overview over the prevalently used automotive protocols with a subjective judgment of the features. To simplify the discussion, only the sensor (slave) to master communication is compared. Complex features with higher risk for safety issues or the need for stronger safety mechanisms are rated negative (-) as well as missing safety mechanisms. Protocol features which focus on an error robust design or error detection methods are rated positive (+). A zero judgment (0) has been given to features which do not belong completely to the positive or negative.

PSI5		DSI		SENT		CAN		FLEXRAY		**PREFERRED FEATURE** UNDER SAFETY ASPECTS
deterministic (time slots)	+	deterministic	+	deterministic	+	non- deterministic	-	deterministic + non- deterministic	+	deterministic
single master	+	single master	+	single master	+	multiple master	0	multiple master	0	single master transmission
unidirectional (opt. bidir.)	0	unidirectional (opt. bidir.)	0	unidirectional	+	bidirectional	0	bidirectional	0	unidirectional
125kHz/189kHz	+	typ: 250-300kHz	+	variable	+	125kHz -1MHz	+	2,5-10MHz	0	lower frequency
Manchester	+	TDCA: 16/27 encoding	+	PWM	-	NRZ	-	NRZ	-	redundant signal coding
parity / 3bit CRC	0	8bit CRC	+	4bit CRC	+	15bit CRC (but bit stuffing issue)	+	11bit + 24bit CRC	+	higher Hamming dist.
high current modulation	+	high current modulation	+	voltage modulation	-	voltage modulation (differential)	0	voltage modulation (differential)	0	robust modulation
fixed start/stop bits	+	n/a	0	n/a	0	multiple fixed bits	+	2 fixed bits per byte	+	fixed bits
initialization phase, free to use bits (i.e. counter)	+	optional: message counter	+	n/a	0	Bit read back, Bit stuffing, Acknowledgement, Error Frames	+	cycle count	+	additional protocol measures

Table 2 Comparison of different automotive interface specifications (see [PSI5], [SENT], [DSI] ,[CAN], [FLEX])

As demonstrated in the above table, the PSI5 interface performs well within the different automotive protocols. Not having the same capabilities as CAN and FLEXRAY, it allows an adjusted level of safety features. The difference to the very similar DSI protocol is negligible. The simple design and robust physical layer further contribute to the safety properties of the PSI5 interface.

3.4 Random faults

Both, random hardware and environmental faults can be influenced by design measures and will have comparable effects within the system. They mainly differ in the way they are provoked. Random hardware faults depend on specific implemented hardware elements and are usually of permanent

existence once they are generated. For the PSI5 interface itself the random environmental faults, which usually are attributed to electromagnetic interference (EMI), are of high importance. EMI upon the PSI5 channel can induce random environmental faults in terms of signal distortions, which again result in bit errors. The incidence of such bit errors is described by the so called bit error probability P_E. Attention should be paid to the fact that EMI induced random faults of system components (that could also lead to random hardware faults or bit errors) are not subject of this discussion due to the fact that circuit chips or building blocks on a chip are defined by specific implementation modalities and differ for each implementation.

4 Bit error models

Coming from a physical point of view, different disturbance characteristics can be distinguished. They are basically defined as (time) continuous distortions and burst errors (limited in their duration). Figure 8 shows the different error models that are considered with respect to environmental random hardware faults. For the noise disturbance multiple parallel noise signals are assumed with normally distributed disturbance levels (Gaussian white noise). In chapter 4.1 the basic continuous noise model is described while in chapter 4.2 and 4.3 different models for noise bursts are discussed. For sinusoidal disturbances (e.g. radio or mobile phone frequencies) section 4.4 describes a model and its solution. Offset errors might result from hardware errors or within a specific system set up as parasitic effect (e.g. voltage drops). However, no separate discussion of offset disturbances is needed as all offset disturbances will safely lead to a Manchester error. For avoidance of offset failure mode, hardware measures (i.e. offset control at the receiver) can additionally be used to improve the availability of the interface.

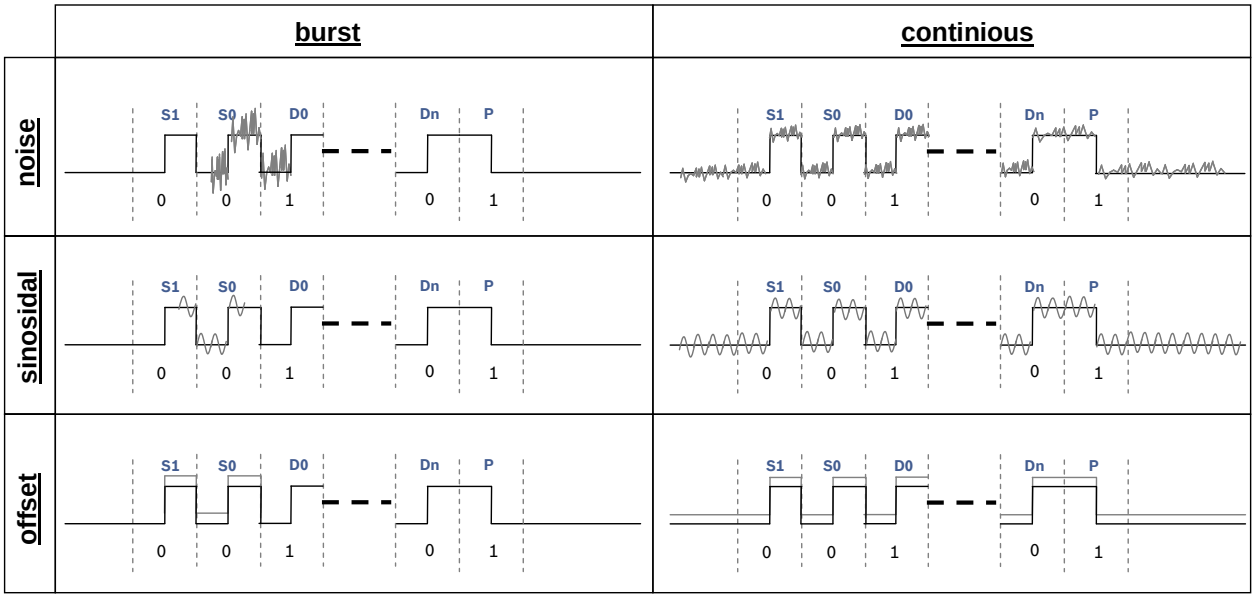


Figure 8 Different continuous and time limited physical disturbance models

4.1 Continuous Gaussian white noise

The PSI5 communication channel under a continuous noise error source is described by the common binary symmetric channel model (BSC, see Figure 9) with additive white Gaussian noise (AWGN)[FRIE].

Main attributes of the BSC are that it is memory-less and symmetric, i.e. the probability for erroneous transmission is independent of former transmission events, whereas the symmetry is given by the same bit error probability for the transmission of both code elements (a “flipped” logical one or a “flipped” zero).

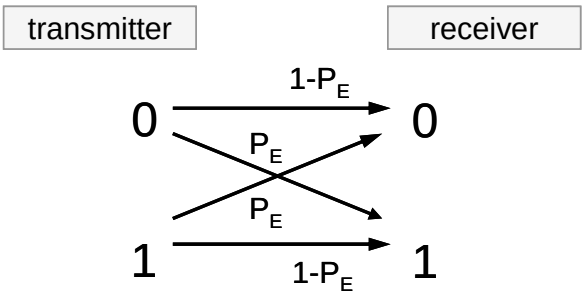


Figure 9 Binary symmetric channel model (BSC)

The probability of transmission of erroneous frames for the BSC channel is given by equation (1).

$$P_{Res} = \sum_{i=1}^{n} \binom{n}{i} \cdot P_E^{\,i} (1 - P_E)^{n-i} \tag{1}$$

with P_E : *probability of halfbit errors*
P_{Res} : *Residual error probability*
(= probability of undetected erroneous frames)
n : *number of halfbits within one transmitted data frame*
i : *number of erroneous halfbits within one transmitted data frame*

For additive white Gaussian noise the bit error probability P_E is a function of the normally distributed noise levels and is given by equation (2) which describes the correlation between bit error probability (more exactly the probability of half-bit errors) and signal to noise ratio (SNR).

$$P_E = \frac{1}{2} \cdot erfc\left(\frac{u}{\sqrt{2}}\right) = \frac{1}{2} \cdot erfc\left(\frac{\sqrt{SNR}}{2}\right) \tag{2}$$

with P_E : *probabilit y of halfbit errors*
signal to noise ratio : $SNR = \frac{A_S^2}{2\sigma_N^2}$
A_S = *signal amplitude (unipolar)* ; σ = *noise amplitude*
note : P_E *is calculated for unipolar signal coding*

In order to determine P_{RES}, the error probability for residual erroneous frames, coverage by the Manchester encoding, the two fixed start bits and the Parity or CRC check bit(s) must be considered. P_{RES}, then, is described by equation 3 and 4 for Parity or CRC covering, respectively.

$$P_{Res} = \sum_{i=4,8,12,\ldots}^{n-4} \left(\binom{\frac{n}{2}-2}{\frac{i}{2}} \right) \cdot P_E^{\,i} \left(1 - P_E\right)^{n-i} \tag{3}$$

$$P_{Res} = \sum_{i=4,6,8,\ldots}^{n-4} \left(\binom{\frac{n}{2}-2}{\frac{i}{2}} \right) \cdot P_E^{\,i} \left(1 - P_E\right)^{n-i} \cdot CRC\left(\frac{i}{2}\right) \tag{4}$$

with P_E : *probability of halfbit errors*

P_{Res} : *Residual error probability*

(= probability of undetected erroneous frames)

n : number of halfbits within one transmitted data frame

i : number of erroneous halfbits within one transmitted data frame

$CRC(x)$: *percentage of " x" bit errors not detected by CRC*

Figure 10 shows the residual error probabilities of the detection mechanisms of the PSI5 interface applied to a NRZ and Manchester Singal Coding with a simplified 10 bit message and additionally P_{RES} for two exemplary PSI5 data frames.

There is already a significant difference in error detection capability between the NRZ and the Manchester code due to the redundant transmission in case of Manchester communication. For the 10 bit PSI5 data-word both coverage mechanisms (Parity or the three bit CRC) have similar impact and even converge for decreasing P_E (increasing SNR) (see also Figure 11). This convergence is attributed to the same Hamming distance of both mechanisms.

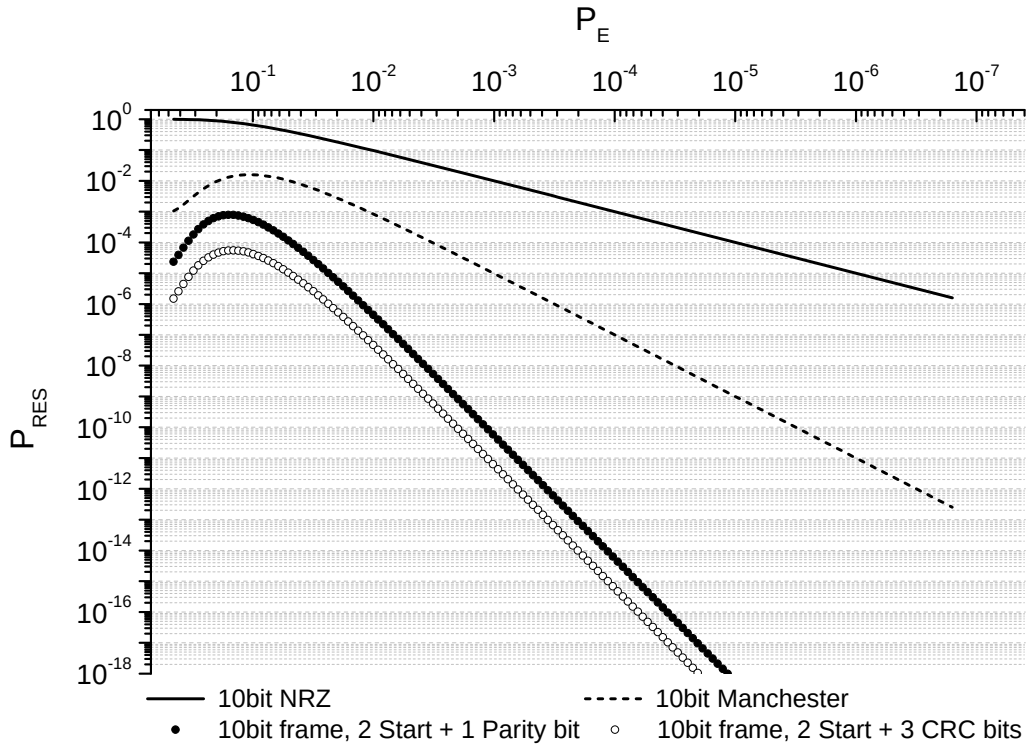


Figure 10 Residual error probability P_{RES} as a function of noise error probability P_E for the NRZ and the Manchester code, as well as two PSI5 data frames

In Figure 11 the half-bit error probability P_E and residual error probabilities of some particular data words are plotted over SNR. It is visible that for signal to noise ratios larger than 8dB the residual error probability of a 10 bit parity protected and a 20 bit crc protected data-word is comparable. For SNRs larger than 14dB the residual error probability is smaller than 10^{-14}.

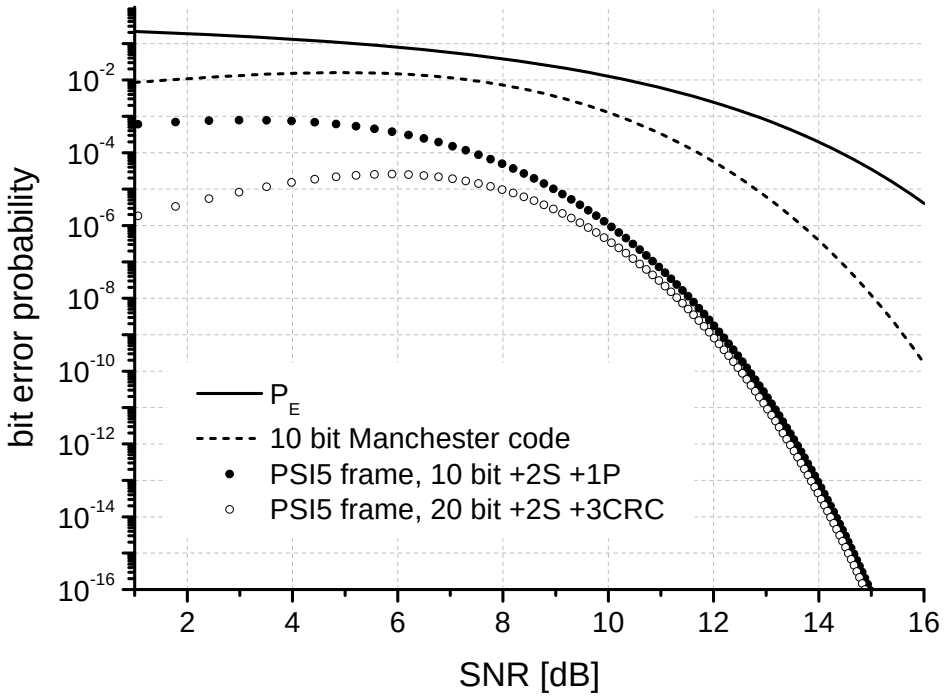


Figure 11 (Residual) bit error probability as a function of the signal to noise ratio

4.2 Gaussian noise burst model

Two burst conditions are distinguished. The first burst model assumes that a burst is present for a complete frame, but not all periodically sent frames are disturbed. The second model assumes that a burst is present within a single frame.

4.2.1 Burst for a sequence of complete frames

The two state binary symmetric channel model (two state BSC, Markov Chain 1st order) describes a channel where transmission is interfered by noise bursts with a minimum length of one data frame. It describes not only error probabilities for transmission (analog to the above described BSC model), but also accounts for the fact that a source of interference is not necessarily of constant existence (see Figure 12) [GILB].

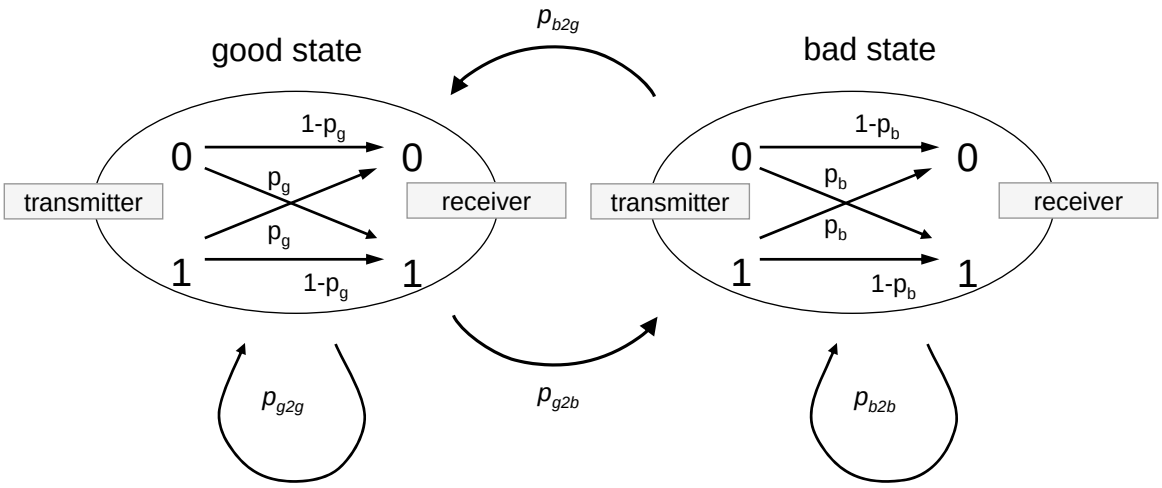


Figure 12 PSI5 channel model: two state binary symmetric channel (BSC) with state transition probabilities Pg2b and Pb2g. Crossover probabilities within the BSC are given by p_b, p_g, (1-p_b) and (1-p_g).

When the channel is in good state, no additional environmental interferer is assumed, and in consequence the bit error probability in the good state (p_g) is much smaller than p_b in the bad state. The resulting residual error probability P_{RES} is given by equation (5). Compared to equation (1) it encounters the two state condition by an additional term which reduces the corresponding error probability derived for the continuous noise model [BORC].

$$P_{\mathrm{Re}\,s} = \frac{p_{b2g}}{p_{g2b}} \sum_{i=4,8,12,\ldots}^{n-4} \left(\binom{\frac{n}{2}-2}{\frac{i}{2}} \cdot P_E^{\,i} \left(1-P_E\right)^{n-i} \right) \tag{5}$$

$$\textit{assumption} \quad : \quad p_g << p_b$$
$$\textit{with} \quad p_b = P_E$$

As the occurrence and extent of EMI induced distortions are widely unknown and the environment of PSI5 networks changes with each specific implementation, a refined and generally applicable model that could give numbers for the state transition probabilities p_{g2b} and p_{b2g} between good and bad state is not reported within the automotive domain. Therefore, it can only be stated that the transmission error probability of the PSI5 channel for the noise burst model is smaller than the transmission error probability

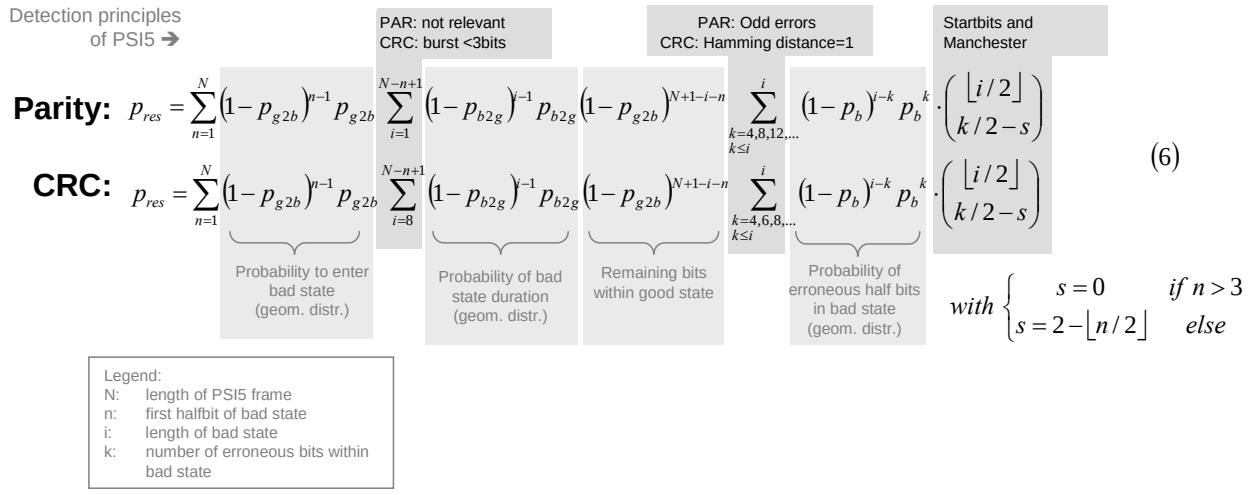
of the continuous noise model, minimized by the factor $\frac{p_{b2g}}{p_{g2b}}$. A range of 10^{-3} has been assumed in that context for the CAN interface. [UNRU]

4.2.2 Burst within a PSI5 frame

Based on the 2-state Markov model shown in Figure 12, failure-bursts within one single frame can also be simulated: State transitions are considered for each half bit, in this case. I.e. for each half bit both, the transition probability and the error probability are considered.

The following assumptions are made: the bad state is entered a maximum of once per frame, since p_{g2b} is considered to be significantly smaller than p_{b2g}. Within the good state the error probability p_g is considered as very small. Therefore, the appearance of any half bit error within the good state is neglected. In the case of data protection by a parity bit, all odd numbers of bit errors are detected. In the case of the 3bit-CRC all frame errors consisting of up to 3 bit failures will be detected, as a low bound approximation (compare to chapter 2.3).

This leads to equation (6) for calculation of P_{RES}. The grey shadowed areas can be divided in the following terms: The probability for entering the bad state, the probability of the duration of the bad state, the probability to stay within the good state and finally the probability to get half bit errors within the bad state. The geometric distribution of the occurrence of bit errors within the bad state is a well suited assumption. Whether this assumption is also suited for the duration of the bad state – as used here - needs to be verified on application level [GILB].



$$p_{res} = \sum_{n=1}^{N} \left(1-p_{g2b}\right)^{n-1} p_{g2b} \sum_{i=1}^{N-n+1} \left(1-p_{b2g}\right)^{i-1} p_{b2g} \left(1-p_{g2b}\right)^{N+1-i-n} \sum_{\substack{k=4,8,12,... \\ k\le i}}^{i} \left(1-p_b\right)^{i-k} {p_b}^{k} \cdot \binom{\lfloor i/2 \rfloor}{k/2-s} \quad \text{(Parity)}$$

$$p_{res} = \sum_{n=1}^{N} \left(1-p_{g2b}\right)^{n-1} p_{g2b} \sum_{i=8}^{N-n+1} \left(1-p_{b2g}\right)^{i-1} p_{b2g} \left(1-p_{g2b}\right)^{N+1-i-n} \sum_{\substack{k=4,6,8,... \\ k\le i}}^{i} \left(1-p_b\right)^{i-k} {p_b}^{k} \cdot \binom{\lfloor i/2 \rfloor}{k/2-s} \quad \text{(CRC)} \qquad (6)$$

$$with \begin{cases} s=0 & if\ n>3 \\ s=2-\lfloor n/2 \rfloor & else \end{cases}$$

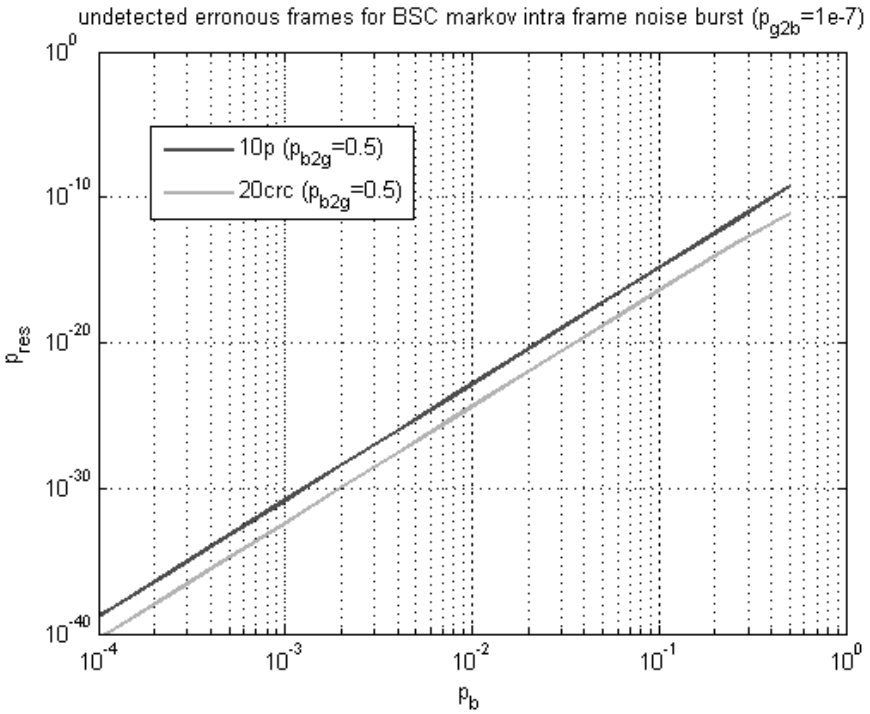


Figure 13 Undetected erroneous frames for the BSC Markov intra frame noise burst model (p_{g2b}=1e-7)

Figure 13 shows some calculation results, assuming suited values for the transition probabilities p_{g2b} and p_{b2g}. Again, frames of 10 data bit, protected by a parity bit, and frames of 20 data bit protected by a 3bit-CRC have been compared. As above, there is only a small gap between the results of the different types of frames. For short bursts (pb2g=0.5) P_{RES} is slightly better for the 20 bit frame with CRC protection. Assuming as one realistic scenario p_b<0.1 and p_{b2g}=0.5 then the residual frame error probability is below 10^{-15}.

4.3 High power Gaussian noise burst

This burst model (see Figure 14) assumes a noise amplitude which is much higher than the PSI5 signal amplitude (about 26mA) and a duration smaller or equal to the length of one frame. The model calculates the percentage of undetected bit errors in dependence of the burst length.

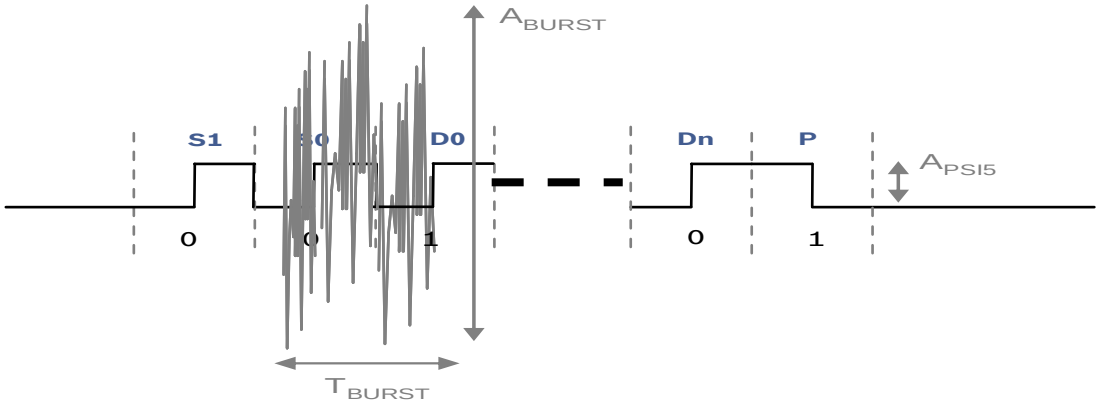


Figure 14 Model of a high power Gaussian noise burst within a PSI5 frame

With this assumption, the probability that a half bit exposed to the noise burst is flipped, is 50% and 50% to stay at its old value. The possible consequences have been calculated for different noise burst lengths assuming a simple two sample point receiver model. However, synchronization problems, which would improve the detection capability because wrong frame lengths would be detected, are excluded from the following considerations.

In a first step the probability of a bit error without Manchester error (both half bits flipped) is calculated. If the burst length is smaller than a full bit, there will be at 50% no effect and at 50% a Manchester error. If the length is as long as a full bit, there are 3 possibilities: at 25% chance no error since the noise burst does not alter both half bits. At 25% there is a bit flip because the noise burst alters both half bits. And at 50% chance there is a Manchester error since the noise burst alters either the first or the second half bit. This calculation can be continued for longer noise bursts in the same way.

From the resulting bit error probability without Manchester error, the probability for undetected bit errors can be calculated very easily for the parity protection. All odd number of bit errors will be detected by the parity check. All even numbers of bit errors will be undetected.

The PSI5 CRC has a hamming distance of two having the same effect as the parity check. Additionally, the bit error burst detection capabilities as described in chapter 2.3 are used. The result is shown in Figure 15 giving the percentage of undetected errors over the length of the noise burst given in units of the length of full bits.

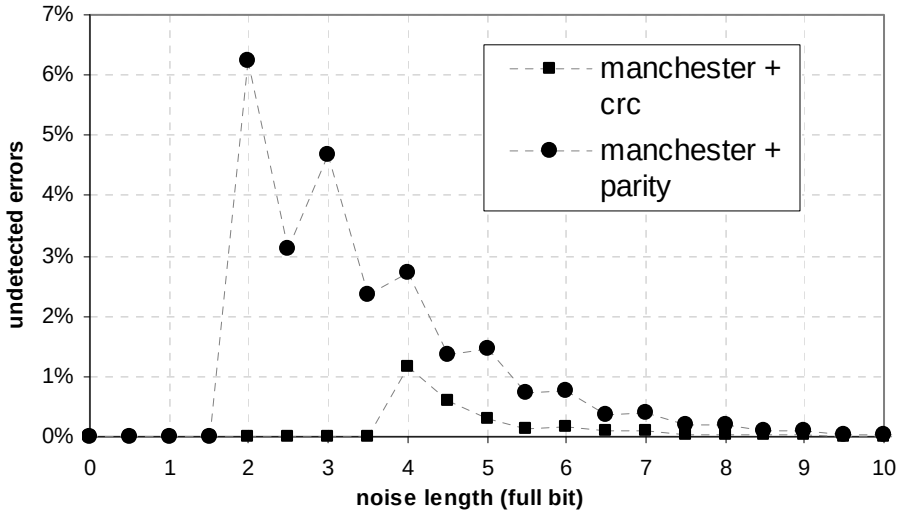


Figure 15 Undetected errors for high power Gaussian noise bursts

Up to the length of 1.5 for the parity check and 3.5 full bits for CRC, respectively, the protocol will detect 100% of all burst errors either by the Manchester decoder or the parity/crc check. For very long noise bursts, the probability that only one of two consecutive half bit flips, becomes very high, so that the Manchester decoder is capable of detecting the corrupted frame. In the case discussed here, the advantage of the CRC algorithm is significant within the range of 1.5 to 6 bits. The highest probability for an undetected error is 6.25%[2] for a burst length of 2 for the parity check and about 1.2% for a length of 4 for the CRC check.

4.4 Sinusoidal continuous disturbances

Besides noise, sinusoidal distortions caused by other electronic devices either intended (i.e. wireless communication) or as side effect (i.e cross coupling on communication lines) may appear. Figure 17 shows how such a distortion can be modeled: a sine wave superposed to the current signal. Additional offset is not considered, but would improve the detection capabilities of the Manchester condition. The sine wave is characterized by a constant amplitude, frequency, and phase over a full frame.

[2] The probability that all four half bits are flipped leading to two flipped full bits not detectable by the parity mechanism is 0,5^4=6.25%.

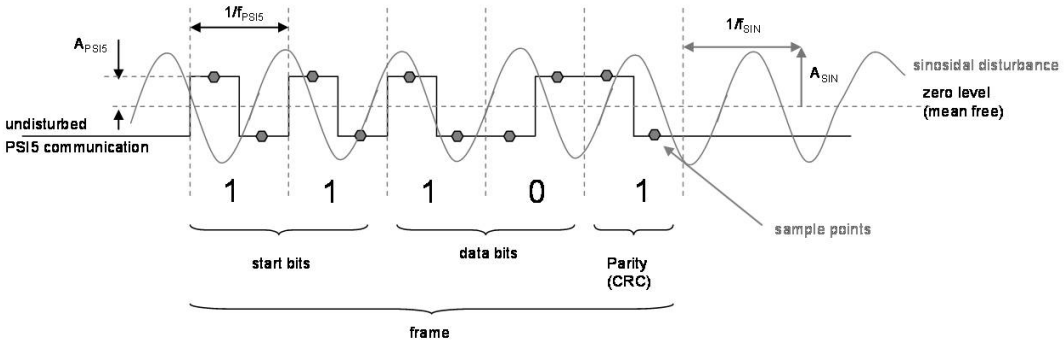


Figure 16 Sinusoidal disturbance model for a PSI5 frame

Averaging over all phases and data words the residual frame error probability can be calculated as a function of amplitude A and frequency f $P_{RES}(A,f)$. As before, a simple receiver model with oversampling factor 2 (one sample per half bit) is assumed.

Figure 17 shows the results, again for a 10 bit frame with parity protection and a frame of 20 data bits and 3bit-CRC. The x-axis represents the relative frequency, the y-axis the relative amplitude. Here, A_{PSI5} is half of the delta between high and low current signal levels, i.e. the distance signal level to detection threshold. The percentage of residual frame errors P_{RES} is given by the intensity of grey out areas. Most frequency ranges are covered by the Manchester decoder, i.e. the Manchester condition is not fulfilled and frame/bit errors are detected. Undetected frame errors are most probable for odd multiples of the PSI5 frequency and only when the amplitude of the sinusoidal distortion exceeds A_{PSI5}.

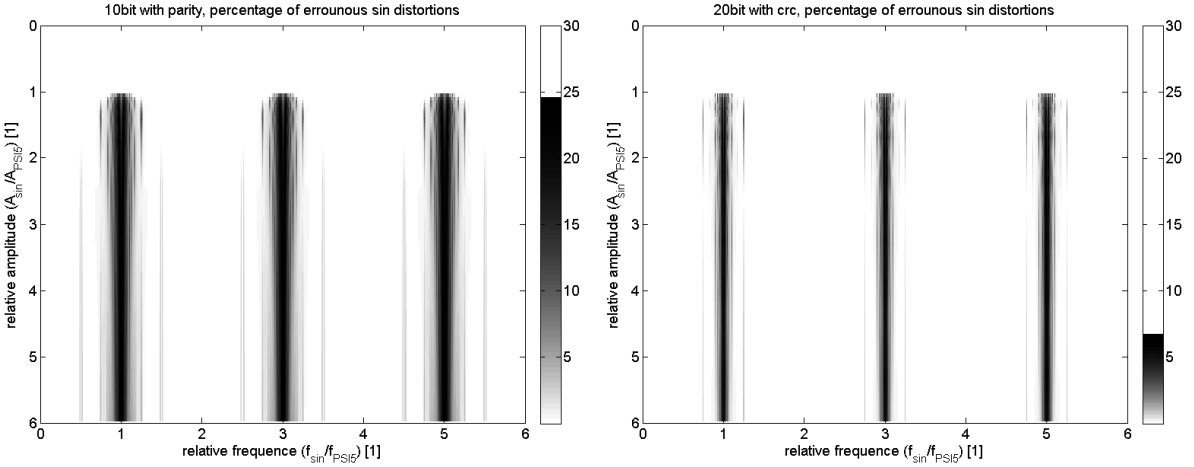


Figure 17 Probability of undetected bit errors in dependence of distortion frequency and amplitude for parity and CRC protection

This calculation model does not consider the gap between single frames. By suited measures at the receiver (e.g. by a check for data within the frame gap or by bit-counting), undetected failures due to sinusoidal distortions which start before, or last longer than, a PSI5 frame can be avoided. Hence, all distortions which last longer than one frame might be detected significantly better.

In case of sine wave distortions with amplitudes below A_{PSI5} the continuous noise distortion models can be used for calculation of P_E / P_{RES} by adopting the SNR accordingly (compare chapter 6.2). Higher distortions are considered unlikely due to the robust current modulation. Nevertheless, such distortions should be avoided. For very high frequencies, the input stage of a receiver represents a low pass filter (e.g. anti-aliasing filter) suppressing the high frequencies making the interface even more robust to high frequency distortions. The cut off frequency depends on the actual design.

5 Measurements

EMI tests were conducted with the main focus on the communication current signal to be checked for distortions on the signal amplitude. The EMI robustness of the PSI5 channel should be quantified in terms of interference amplitudes and signal to noise ratios. In order to receive quantitative measures for electromagnetically induced deviations of the transmission signal that don't necessarily lead to data failures (bit errors) a specific channel replica has been built in a way to exclude as many hardware dependent influences as possible. It is schematically shown in Figure 18.

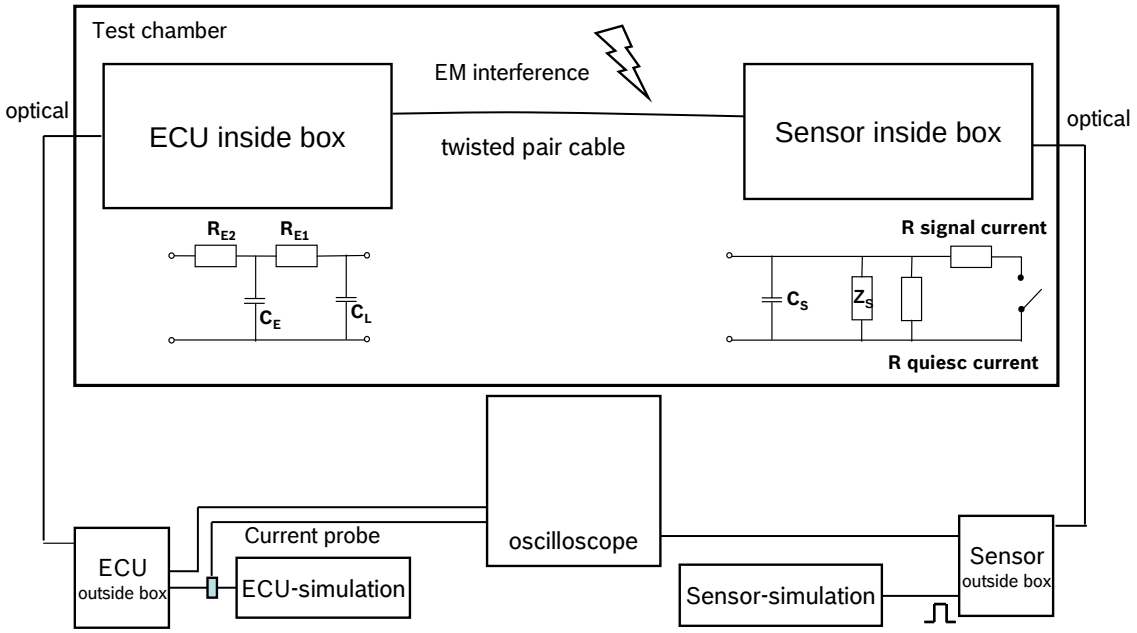


Figure 18 EMI test assembly

The typically measured signal shapes at sensor output and receiver input are shown in Figure 19. The slight signal distortion even with no external EMI, which can be seen at the receiver input, is attributed to artefacts caused by the double signal conversion to optical and back to electrical transmission. Additionally, a slight signal rounding due to cable resistances and inductances is observed.

The noise shown here upon the signal amplitude is attributed to transmitter noise and measurement artefacts of the current probe rather than to environmental noise.

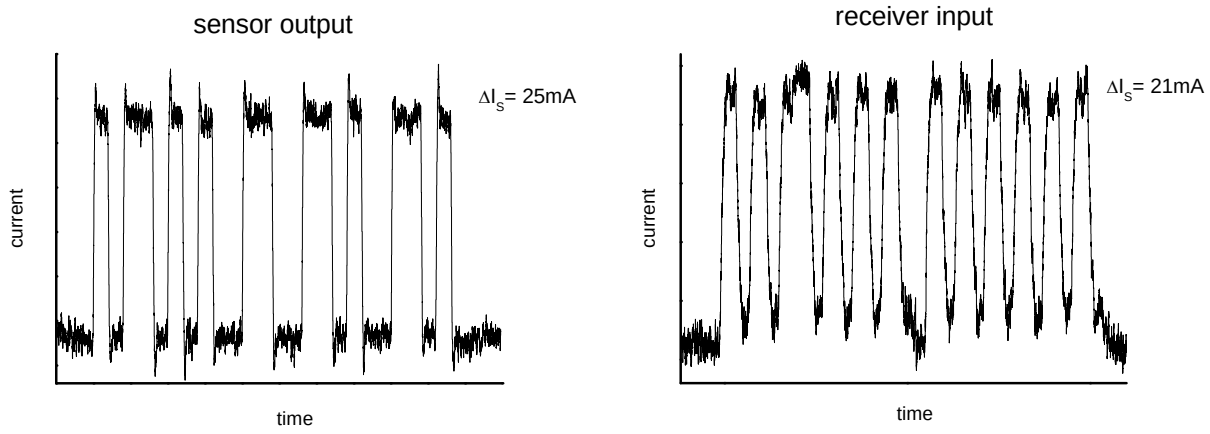


Figure 19 Modulation current measured by the current probe at sensor simulation output and ECU simulation input.

The following test procedures have been applied to the channel replica:

- Bulk Current Injection (BCI)
  1-400MHz; see [EMC1] and [AKLV]
- Absorber Lined Shielded Enclosure (ALSE)
  200MHz-1kHz; see [EMC2] and [AKLV]
- Transients On Lines other than supply lines (TOL)
  up to 200V applied onto twisted pair cable; see [EMC3] and [AKLV]

Transients on Supply Lines (TSUP) have not been considered systematically because PSI5 supply and signal lines are always laid as a twisted pair and hence, TSUP tests do not reflect real application cases. Table 3 gives an overview of the parameters tested.
Measureable impacts on the PSI5 twisted pair cable could only be found after exceeding the standard automotive test ranges. Thus, for instance, the maximum applied distortion intensity has been significantly extended for all tests compared to the maximum values given in the referred standards. E.g. ±750V for transient measurements compared to maximum values between -75V and +40V stated in the ISO standard or the VDA document, respectively. This value is even higher than the maximum pulse intensity given in TSUP configuration (-150V to -100V, [EMC4]). Furthermore, BCI coupling was only seen in differential mode when the electromagnetic interference was applied to one line of the untwisted cable, which is contrary to the implementation.

test parameter	intensity	standard*)	modulation current ΔI_S
BCI closed loop 1-400MHz CW and AM (1kHz)	200-300mA	ISO 11452-4 VDA AK-LV 27 & 29 part 3	10-25mA
			10-15mA
BCI open loop AM (1kHz)	255mA @ 80MHz	ISO 11452-4 VDA AK-LV 27 & 29 part 3	10mA
	255mA @ 145MHz		
Antenne 200-1000MHz CW, ho/ve	200V/m	ISO 11452-2 VDA AK-LV 27 & 29 part 3	10-20mA
transients	+/- 200V	ISO 7637-3 pulse 3a), 3b) VDA AK-LV 27 & 29 part 3	10-15mA
	+/- 500V		
	+/- 750V		
	+/- 6V	ISO 7637-3 pulse 1, 2 VDA AK-LV 27 & 29 part 3	15mA
	+/- 20V		
	+/- 40V		
	+/- 50V		
Honda Noise Test	+/- 2kV	square-puls, width 200ns, interval 33ms, impressed via coupling clamp (± 2kV, ratio 1 to 10)	10mA

Table 3 Summary of the conducted EMI tests.
**)Test parameters were chosen in accordance with the named ISO, or VDA standards, respectively. In all cases interference amplitudes were applied with significantly higher values than defined in the aforementioned documents - but still without measureable impact.*

A typical measurement result for the BCI measurements (interference applied upon the twisted pair cable) is shown in Figure 20.

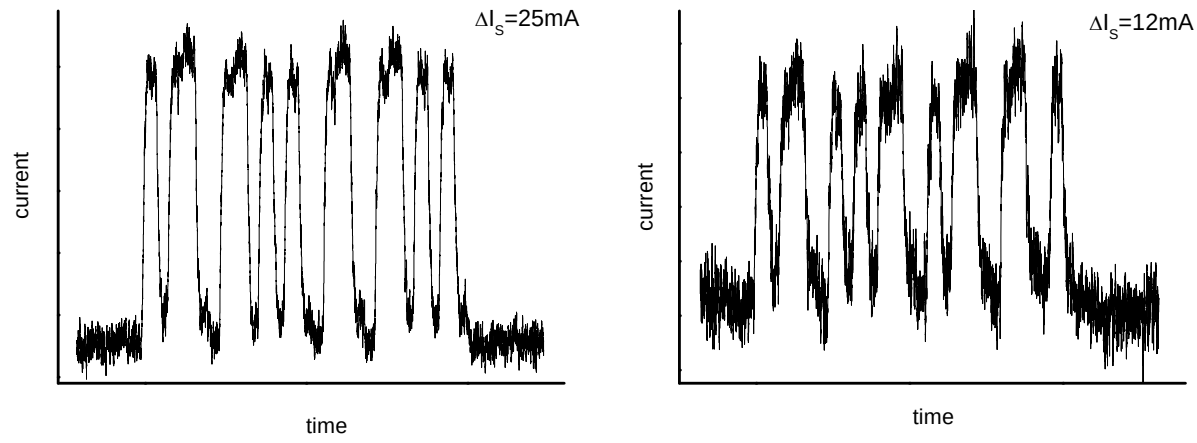


Figure 20 Modulation current measured by a current probe at ECU simulation input under application of BCI distortion (300mA, 20-50MHz)

Taking the present signal to noise ratio of the BCI measurement - even if no high frequency inductive coupling was detected, compared to the measurements with no external distortion – the residual error probability can be calculated using equation (1); for a modulation current of 25mA a signal to noise ratio of 25 dB is derived leading to a negligibly small residual error probability. For a modulation current of 12mA, the residual error probability is in the order of 10^{-19} (the corresponding SNR is ~16dB).

Regarding the transient measurements, additional pulse amplitudes upon the transmitted current modulation signal could only be generated by pulse distortions of ±750V. An example is given in Figure 21. Even for significant voltages applied, the coupled transient is not large enough to lead to erroneous signal detection. And due to the fact that the duration of the interferer is in the range of t_{bit}, errors will be detected by the Manchester decoder, as well as by the CRC or parity check. Consequently, the transient signal measured in the experiments never lead to detected data errors.

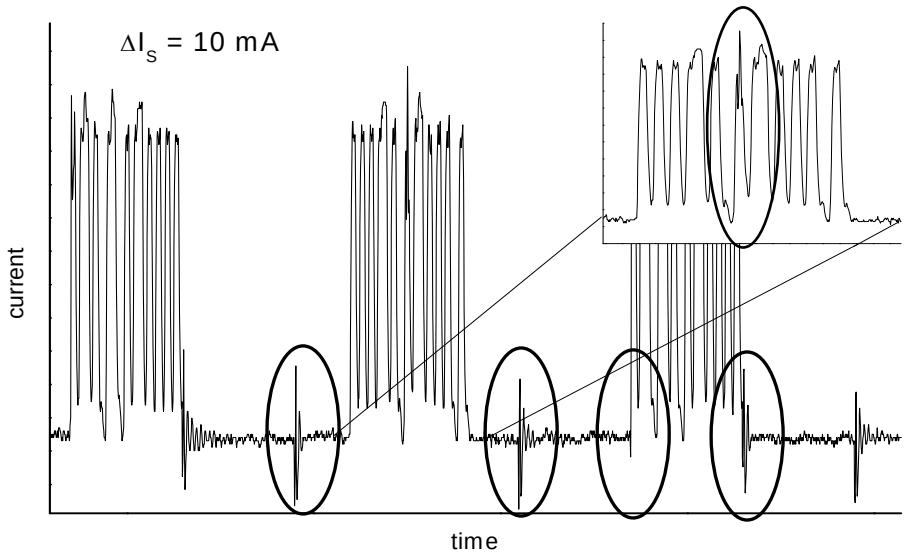


Figure 21 Modulation current measurement under application of a pulsed interference conforming to ISO 7637-3 (test pulse 3 a) at 750V) No data failure detected in experiments (depends on receiver implementation, i.e. current level detection threshold)

Finally, it has to be emphasized that the experiments aimed to characterize the PSI5 interface in itself. Thus, the interface replica was designed as described above. Different results might be found for the same EMI tests when real systems, including sensor and receiver hardware, are tested, and additional coupling paths, e.g. via circuit elements on the chip, can occur.

6 PSI5 interface integration

Previous chapters have been made as precise as the generic PSI5 specification allows. For an effective integration of the PSI5 interface into a specific system, several further aspects have to be considered with respect to safety requirements. It has to be verified, for example, that the PSI5 specification meets the needed communication requirements, the actual hardware designs have to be conform, the interface has to be integrated into the system and the actual PSI5 and system metrics have to be calculated. The following sections give hints on further aspects to be considered.

6.1 Hardware implementation aspects besides EMI

Noisy transmission signals alone, as shown in chapter 5, are of low risk for safe PSI5 transmission. But for a given implementation additional effects need to be taken into account.

Depending on specific system constraints the signal shape may differ from ideal rectangular PSI5 signals. Considering the current slope of the sensor, the damping characteristics of both the input interface of the ECU and the sensor, and the wiring inductance and wiring resistance (i.e. type and length of the cable) can lead to a signal as schematically shown in Figure 22. In consequence, signal over- and undershoots need to be considered as real signal characteristic.

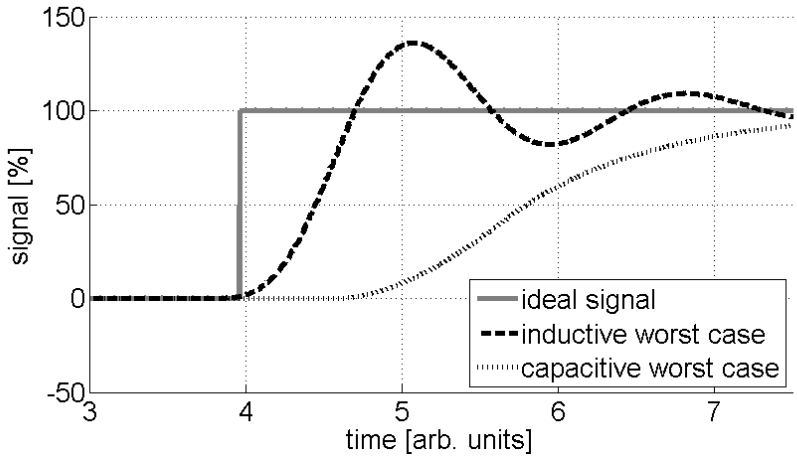


Figure 22 Example for inductive and capacitive signal characteristics of a communication link

Ripples on the supply voltage can also cause a current ripple depending on the input interface circuit, the signal may also be distorted due to coupling from other PSI5 channels and finally tolerances of the detection threshold need to be regarded.
All these implementation aspects can be considered for SNR calculation according to the following equation (7):

$$SNR' = \frac{(A_s - a)}{2\sigma^2_{eff}} \quad with \quad \sigma_{eff} = \sqrt{\sigma^2 + \sigma^2_{impl}} \tag{7}$$

For any effect which reduces the signal distance, we can reduce the signal level A_S by an implementation dependent amplitude a. Considering additional impacts on signal level that can be modeled as noise with approximately Gaussian distribution, the standard deviation σ can be adopted to an effective noise level σ_{eff} by adding an implementation specific noise term σ_{impl}.

6.2 Calculating residual error rates for an actual system

This chapter will give an example approach to calculate the bit error rate for an implemented system that is exposed to continuous Gaussian noise (see chaper 4.1). Implementation aspects considered are: the nominal quiescent and signal current levels, possible signal ripples, over- and undershoots within the individual system, the tolerance range of the detection threshold and potential coupling of other signals. The reduced SNR level (increased noise / reduced distance of relevant signal levels for calculating the error probability) is included in the calculation of the half-bit error probability p_E according to equation (2).
We consider a typical airbag application (two start, 10 data bits, one parity bit and at least one stop bit): the nominal distance between quiescent and signal current level is 26mA, the minimum value is 22mA. Typical noise shows a standard deviation below 1mA. For the exemplary implementation case, the SNR is adapted by reducing the delta current by 10mA and increasing the noise standard deviation up to 1.5mA. Based on the so calculated half-bit error probability of $P_E=3\cdot10^{-5}$ the residual frame error rate P_{RES} after Manchester decoding and parity check, is below 10^{-16}. With 2 kHz data rate, and the assumption that a single corrupted undetected frame violates the safety goal on system level, A residual failure rate $<10^{-10}$ of undetected failures per hour is derived.

More intelligent receiver designs, which do not just use two point sampling, will render the values even better. For most systems a single frame error will not be safety critical. When assuming that at least two (consecutive) corrupted frames have to remain undetected, the residual failure rate for above example drops to below 10^{-20}/h which seems to be out of scope to be considered.

Following the above considerations, which is considered as worst case example, the PSI5 interface will not be the safety critical element within an ASIL D system. However, the confirmation has to be made on a system level since there may be other faults (hardware faults of all parts of the system) which additionally contribute to the safety metric target.

6.3 ISO26262 conformal calculation of relative metrics

The ISO26262 requires the consideration of an absolute failure metric (Probabilistic metric for random Hardware Failures (PMHF)) and two relative metrics (Single-point fault metric (SPFM) and latent-point fault metric (LPFM)). The PMHF can be calculated using the failure rate of the PSI5 interface as exemplary shown in chapter 6.2.

The SPFM for the safety goal is specified as the quotient of all undetected single faults and all faults at all. According to equation C.5 in Part 5 of the ISO26262 and applying the calculation example of chapter 6.2 the following result is achieved: The overall failure rate of the PSI5 interface is very high (i.e $\sim\lambda_{PSI5}=2.2\bullet10^{+2}$/h for $P_E=3\bullet10^{-5}$ with 2kHz sampling) compared to other hardware elements (typically much below $1\cdot10^{-8}$/h) But the residual failure rate ($\lambda_{res,PSI5}=10^{-10}$/h), again, is comparable to other hardware elements. Thus, the SPFM of the system would be misleadingly determined by the PSI5 failure rate. Due to this effect, inclusion of the PSI5 interface in the relative SPFM should be avoided.

The LPFM is the second relative metric which shall be considered according to the ISO26262. An example for a latent fault within the PSI5 interface would be a wrong quiescent current. If this current drops below the specification, the system might still work correctly, however, the SNR ratio drops significantly resulting in a degraded EMI robustness. Such failures should be included within the considerations of systematic faults of the hardware elements (which are application specific) and the calculation of their LPFM.

Hence, it is adequate to include the PSI5 interface in the absolute metrics but not in the relative ones. However, it might explain the following statement of the ISO26262: “These quantitative target […] do not have any

absolute significance and are only useful to compare a new design with existing ones”.

7 Summary and Conclusions

Within this paper the application of the ISO26262 to the new PSI5 specification 2.0 is discussed with a practical background considering systematic and random faults.

PSI5 provides many means for systematic error avoidance and detection, both on physical and on data link layer. The considerations have shown evidence that all systematic effects can be well handled by the PSI5 interface.

For conformity considerations regarding the ISO26262, the probability of undetected random hardware failures needs to be assessed. Within this paper the probability of undetected environmental random faults is emphasized and several models to calculate the residual frame error probability have been presented. Furthermore, offset failures are uncritical due the Manchester condition, as well as sinusoidal disturbances are uncritical up to a certain disturbance level.

Measurements have been conducted and the results were used to parameterize the theoretical models to real world environments. However, these experiments show that the effects of “real world disturbances” upon the PSI5 line (as reproduced by the applied test procedures) are so small that all applied models are in a range where practically no errors are present. In other words, there are no disturbances to be detected due to the robust interface.

Regarding new, low current operation modes as optionally specified for the power train substandard, the definition of the current levels plus constraints regarding the implementation (e.g. tolerance with respect to the detection threshold, maximum signal ripple, etc.) will mainly define the values P_E and P_{RES}. Referring to the measurement results of chapter 5, the lower signal levels itself still make individual safety applications conceivable, but need to be investigated thoroughly with respect to their effective implementation and resulting constraints.

Summing up, all aspects suggested by the ISO26262 have been analysed and several methods were presented to handle the possible faults. The application standard protocol definitions seem to be well suited for their intended applications.

Overall, the presented methods support conformity considerations regarding ISO26262 for systems rated up to ASIL D. However, the final judgment on

functional safety of a system is always subject to an application and implementation specific safety analysis and can only be done on system level.

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