Quality of Profibus Installations

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Abstract

Reports of Profibus-DP installations in the industry show unexpected transmission errors. If we analyze the Profibus error detection and correction mechanism and the possible reasons for these transmission errors, it is possible to understand this phenomenon. We show how to measure these transmission errors and how to improve the quality of a Profibus-DP installation.

1. Introduction

Since more than 15 years Profibus installations are used in a growing range of applications. Up to today about 15 Millions of dedicated Profibus ASICs are build into different products. Manufacturers equip their machines with this technology and ship it around the world.

In the last year we got several requests and questions about the possibility, that the Profibus network transmits wrong values, without signaling it to the application program. A sensor in the machine measures and transmits always the correct value, but the controller receives a wrong value. This event happens only once in several days or once a week. So it is very difficult and time consuming to fetch such an error and it is impossible to reproduce the error in a laboratory setup. It happens only in the field, and only on some of the machines. This type of error is disturbing the end user.

Our Profibus Competence Centre was able to solve these problems. The source and mechanism of this type of problem is analyzed in this paper. First we outline how transmission errors are detected and corrected in Profibus, and then we list the most common sources for these errors. In the third section we give some guidelines on how to measure and make the diagnostics of a Profibus network and we close with a list of conclusions.

2. Transmission errors

Profibus-DP is typically a single master system. So we focus on the user data transmission only. The Profibus-DP protocol is able to detect transmission errors and to correct the transmission errors with the automatic repeat-request (ARQ) mechanism.

2.1. Definitions

The bit error rate P is the number of erroneous bits in relation to the number of all transmitted bits on a communication system.

$$P = \frac{number\ of\ erronous\ bits}{sum\ of\ all\ transmitted\ bits} \quad (1)$$

In the worst case is P = 0,5 and every second bit is wrong. In practical applications P = 10^{-4} is feasible. According to [10] and [11] a shielded twisted-pair telephone cable has a bit error probability of 10^{-5}. Profisafe assumes in [9] that the same value applies also for a Profibus installation.

An error detection mechanism has to detect these transmission errors. But there is still a chance, that not all erroneous bits are detected. The residual error rate R is defined as the number of undetected erroneous bits in relation to the number of all transmitted bits.

$$R = \frac{number\ of\ undetected\ erronous\ bits}{sum\ of\ all\ transmitted\ bits} \quad (2)$$

The relation between the P and R defines the Integrity Class of the error detection mechanism. Integrity Class 1 is considered as sufficient for cyclic data exchange, integrity class 2 for event driven communication and integrity class 3 for remote control systems. Figure 1 shows the relation of R and P in logarithmic scales and the regions of the Integrity Classes according to [14].

The hamming distance H is an indication of the error detection possibilities of a code. It is represented by the slope of the region in Figure 1. You will find for two points P_1 and P_2 on the function

$$H = \frac{\log(R(P_1)) - \log(R(P_2))}{\log(P_1) - \log(P_2)}, P_1 < P_2 \quad (3)$$

So the limit of Integrity Class 1 is H = 2 and the others require H = 4.

The medium time between two undetected transmission errors T_E can be calculated based on R, the bit rate v and the numbers of bits in a frame n:

$$T_E = \frac{n}{v \cdot R} \quad (4)$$

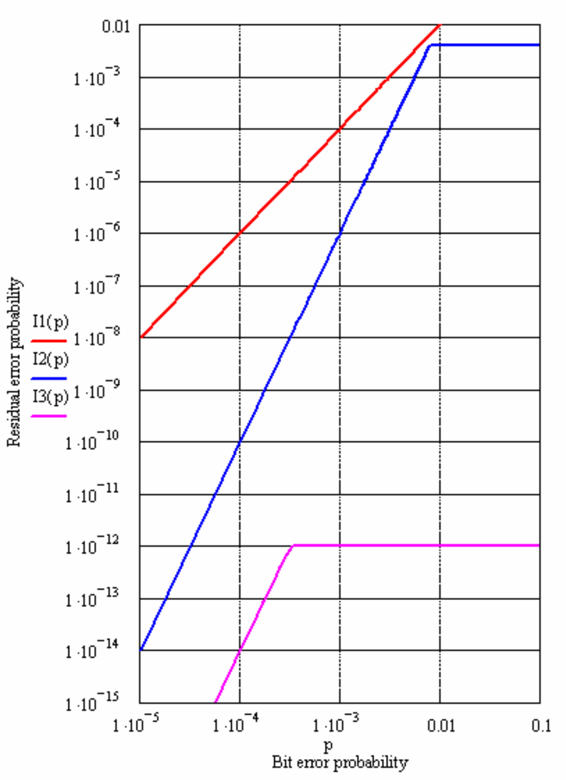

Figure 1. Logarithmic relation between R and P

Based on these relations it is possible to calculate the expected time between two undetected transmission errors also in a Profibus system.

2.2. Detection of transmission errors

One transmission frame of Profibus is composed of different octets. Every octet is transmitted in the asynchronous way with start, stop and an even parity bit as shown in Figure 2. The parity bit is used for error detection: if the parity of one octet in the received frame is wrong, the whole frame is ignored by the receiver. With this parity check only 50% of all transmission errors may be detected (H=2).

Start	Bit 1	Bit 2	Bit 3	Bit 4	Bit 5	Bit 6	Bit 7	Bit 8	Parity	Stop

Figure 2. Octet with even parity

For data frames an additional checksum is used. The sender calculates over the defined part of all transmitted data's the arithmetic sum of all octets, ignores the overflow and send this octet as a Frame Check Sequence (FCS) at the end of the frame. The receiver does the same calculation. If the FCS is not correct, the whole frame is ignored. If we have two undetected errors in two octets in one frame, there is a chance, that the FCS is correct again. With this method Profibus reaches hamming distance four (H = 4), so at least four bits have to be modified, to get another valid frame.

The frame with start delimiter 2 (SD2) is shown in Figure 3. A typical data frame (SD2) has at least 132 bits length for 1 byte of user data or at most 2805 bits length for 244 bytes of user data.

SD2	LE	LEr	SD2	DA	SA	FC	PDU	FCS	ED

arithmetic sum

SD2 = Start Delimiter 2 (value 0x68)
LE = LEngth of the frame
LEr = repeated length of the frame (same value as LE)
DA = Destination Address
SA = Source Address
FC = Function Code
PDU = Protocol Data Unit (the user data)
FCS = Frame Check Sequence
ED = End Delimiter (value 0x16)

Figure 3. SD2 Frame structure and FCS

In [14] the formulas that specify how to calculate the relation between P and R for a frame of the Profibus construction are given. The combination of the different error detection mechanism, the parity check, the sum over a part of the frame and the format specification for all the octets, gives a complex formula. In Figure 4 the results for 1, 30 and 244 user data octets are plotted. Profibus is clear inside the Integrity Class 2, but the error detection possibilities depend on the number of user bytes as expected.

If there are no error detection mechanism with P= 10^{-4} and a frame every 2 ms this would lead to a transmission error every 87 seconds. With the error detection mechanism of Profibus, this results in a residual error rate R depending the number of data bytes transmitted in the frames. Figure 4 gives for the case of 30 bytes data the residual bit error rate of 10^{-12}. So an undetected error will occur only every 1'002 days. It takes more than 3 years for an error to get undetected in this type of cyclic frame.

2.3. Correction of transmission errors

Transmission errors are corrected with automatic repeat-request (ARQ). In the Send and Request Data with acknowledge (SRD) service, the sender waits for an immediate replay by the responder. If this reply is timed out, the sender repeats the message as shown in Figure 5.

After a specified number of retries, the sender signals the failure to the user application. The IEC 61158 standard [3,4] specifies a maximum of 8 retries, in special test cases also 15 are allowed. The user has the possibility to modify this parameter on the setup of the system. If there are retries in the Profibus network, this is handled automatically by the communication interface and the user application gets informed only, if there are more than 8 unsuccessful requests in sequence.

It is also possible that the reply gets lost. For this case there is a need to number the sending frames that the receiver may differentiate the original frame from the repeated frame. This is done in the Profibus protocol with the Frame Count Bit (FCB). The Frame Count bit Valid (FCV) indicates if the frame count is used. On the first request frame, the frame count has to be initialized with a sync message frame (see Table 1). If a frame is repeated, the same FCB is used as shown in Figure 5.

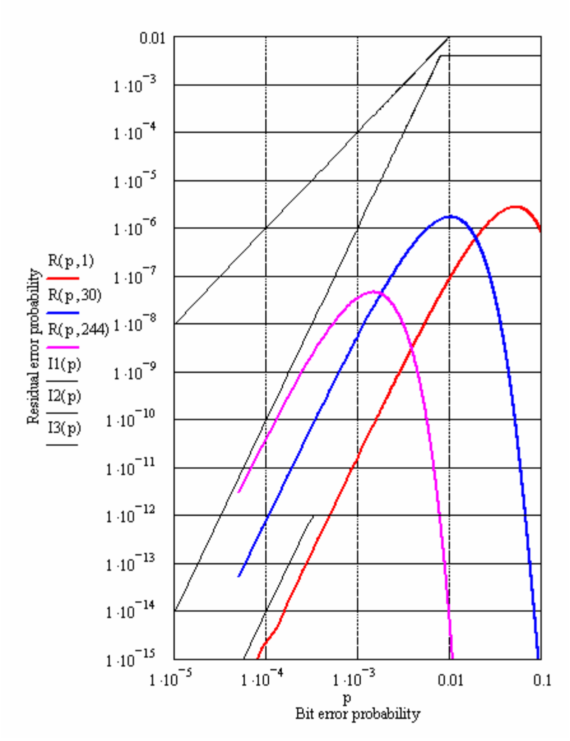

Figure 4. Relation of R and P for Profibus SD2

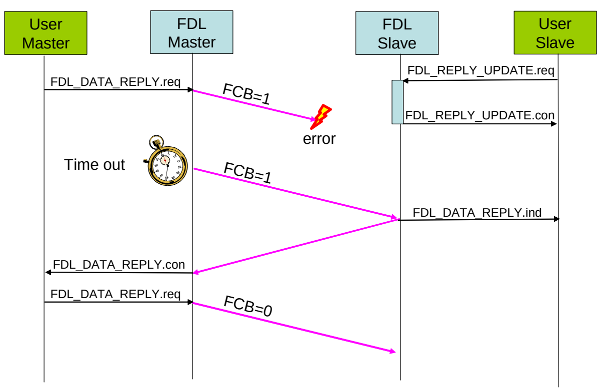

Figure 5. SRD Service with ARQ

In the link layer management exists the possibility to add counters for erroneous and correct frames transmitted and received. But most devices have these counters not implemented or these counters are not accessible to the end user.

Table 1. Meaning of the frame count bits

FCB	FCV	Meaning
0	0	Service without acknowledge
1	0	First acknowledged frame (sync)
0/1	1	Counting acknowledged frames

3. Reasons for errors

There are different sources of transmission errors in a Profibus network. The installation may be outside the permitted range or there are external electromagnetic noise and disturbance influencing the data transmission.

3.1. Cable installation

The typical electrical transmission of Profibus is based on the RS 485 [13] recommendation. There is a symmetric two wire transmission, with a cable with a typical impedance of 150Ω ±10% specified in [2]. To eliminate the reflections at the end of the cable, there is a termination with 3 resistances defined. Every device connected to the Profibus shall have a power output at his connector as listed on Table 2 for the D-Sub 9 connector.

Table 2. Pin Assignment of D-sub connector

Pin no.	Signal	O/M	Meaning
1	Shield	O	Shield / protective ground
2	M24	O	Ground for 24V output
3	Line B	M	Data plus
4	CNTR-P	O	Repeater control plus
5	DGND	M	Data ground (to 5V)
6	VP	M	Supply voltage(5V)
7	P24	O	Output voltage 24V
8	Line A	M	Data negative
9	CNTR-N	O	Repeater control negative

O = Optional M= Mandatory

The termination is used to define the potential level on the line if there is no signal active. So the exact termination on the line is only available, if the power of the termination is switched on. The termination is calculated as

$$R_T = \frac{(R_1 + R_3) \cdot R_2}{R_1 + R_3 + R_2} = \frac{(390 + 390) \cdot 220}{390 + 390 + 220}\Omega = 171{,}6\Omega$$

and is on the upper limit of the impedance of the cable. If the termination is not powered, the R_T does raise to 220 Ω. This will result in reflections. Figure 6 shows a typical setup of such a line.

The first version of Profibus according to the DIN 19245 standard [1] defined a different cable with 120 Ω ±10% impedance and different values for the line termination (R_2 = 150 Ω). If old and new installations are mixed, this will cause also reflections on the line.

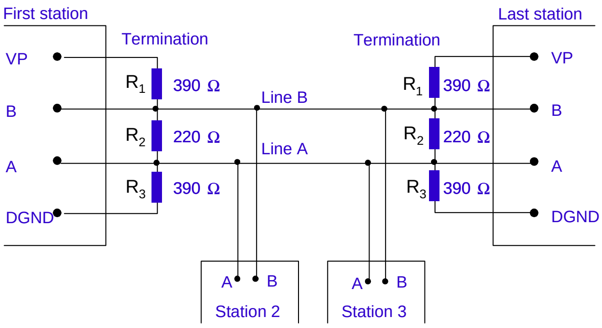

Figure 6. Line setup with terminations

A Profibus network is not able to run, if not at least one of the terminations is powered: The electrical potential level is undefined and the electrical potential can drift away to any value. This may even destroy the connected equipment.

The signal propagates with a speed of about 2/3 of the light speed in this type of cable. So for a distance of 1 meter a signal needs about 5 ns travel time. For a bit rate of 12 Mbit/s a maximal length of the cable of 100 m is allowed. This results in a maximal travel time of 500 ns for one way. The value of the bit is verified by the receiver in the middle of the bit duration. So if the travel time is in the order of half of the bit duration, reflection may influence the interpretation of the bit and cause transmission errors. The duration of one bit depends on the bit rate used. With the bit rate of 12 Mbit/s the duration is 83 ns. A cable of more than 8 meters may already cause reflections with transmission errors.

The influence of reflections is reduced through the cable length. The cable has attenuation. This attenuation reduces not only the signal, but also the reflection. Profibus is a bus topology, but this does not mean that you see in any case on every point of the bus the same signals: the cable is a line and follows the rules of the transmission line. You do not measure on all point of a bus the same signal due to these attenuations.

3.2. External disturbance

Profibus specifies in [7] very clear that shielding and grounding of the shield of the Profibus cable is mandatory. How this should be done is explained exactly and in details in the recommendation [5]. The requirement [8] defines how these installations should be tested. If there are transmission errors detected in the field, most of the time this was due to a bad cabling like

- no, too much or wrong termination
- wrong cable specification
- shielding or grounding not according the rules
- minimal distances to power lines not respected
- potential differences between different parts of the installation

Measurements in different installations in the field by our and other competence centres showed that if these rules are followed and the installation is made correctly, there are no problems with external disturbances.

4. Diagnostics

To verify the quality of a Profibus network we can look at the frames and at the electrical signal forms.

4.1. Check the electrical signals

Reflections and disturbances can be checked in the simplest way with an oscilloscope. As we have differential signal we need an oscilloscope with two channels and the mathematical subtraction function to get the relevant signal. In principle it is also possible to use an oscilloscope that is able to measure independent from the ground. But in this case the ground connection is very often not with high impedance and may influence the system to be measured. So we recommend to measure both lines with high impedance probes and to calculate the difference. This allows in the same time to verify both signals.

The problem with the oscilloscope is the triggering of the scope. A simple trick is to take the repeater control signal of the D-sub connector of the device (see Table 2). The signal gets active if and only if this device is sending. So it is possible to measure the transmission signal of this device. Unfortunately this signal are only optional and not supported by all devices. With this method it is only possible to measure the level of the sending signal of this station: It is not possible to trigger on the receiving signals.

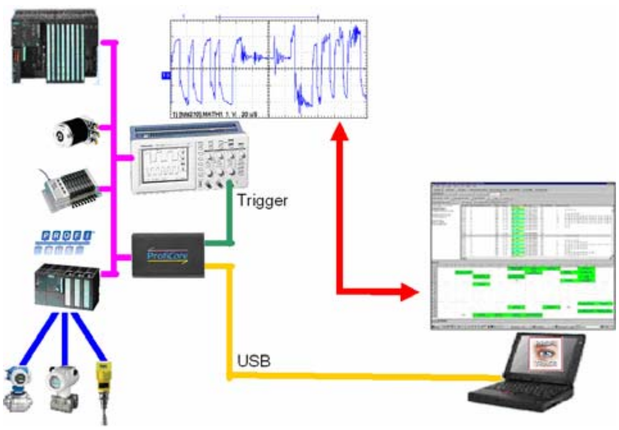

Figure 7. Setup of measurement

If we want to see the signal from every device on the Profibus network as a separate drawing we need an additional tool. We need an analysing tool that generates a trigger signal depending a sending address on the frame itself (octet 6 in Figure 3). One solution is to use the ProfiTrace tool [12] in a setup as shown on Figure 7. The user clicks on the live-list on the required station and the ProfiCore box sends the trigger signal if a frame with the corresponding address as source address is passing on the bus.

Figure 8 shows a scope with reflections on the end of the cable. It is clear, that it needs some experience, to do the correct interpretations of such signal captures in practical installations. Guidelines of such interpretations are given in [5].

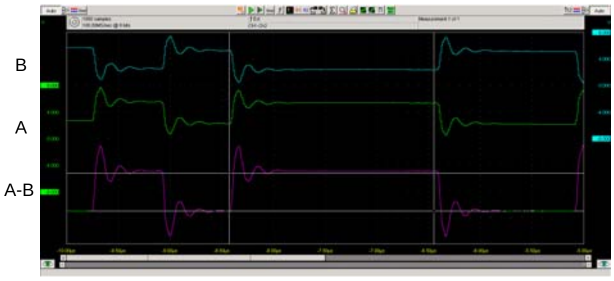

Figure 8. Scope of signal with reflections

4.2. Check the frames

To verify the frames on a Profibus network exist different commercial tools. In fact, every serial Universal Asynchronous Transmitter Receiver (UART) that is able to handle the bit rate is able to fetch the Profibus frames and to monitor the bus.

For the test of the quality of the frames we do not need a complete registering of all transmitted octets. We need some statistical information: how many frames are detected with parity errors or wrong checksums.

But this information may not be enough. It is possible, that on the point where we measure on the network, the frame is still of good quality and on another position on the cable it is distorted by reflection or external influence. In this case the frame is not received by the responder and there will be no reply. The sender does repeat the request. So we need additional statistics about the number of repeats on the network. A good indication is also, if we count the sync frames for the bit count of the frames. In an error free Profibus network there should be no repetitions and only one sync frame at the start up of the system.

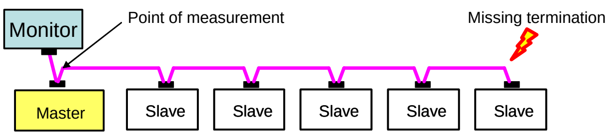

Figure 9. Example of measurement topology

If we just rely on the count of the frames with transmission errors we may be completely wrong with our measurements. Let us explain this on an example: if we measure close to the master (see Figure 9) of an installation, the signals send by the master are all of good quality. But the problem of this installation is the wrong termination at the other end of the line. The frames are not recognised by the last station on the line due to reflections. At the point of measurement, these reflections are already attenuated and the frame is still correct. The only possibility is to look at the retries: If the last slave on the line does not receive the frame there will be a retry by the master. So the best statistical information about the quality of the network is the number of retries.

It is important to know who does not reply or who has resynchronisations! If we compare this statistics with the location of the station on the cable we can better understand where the location of the error is and what could be the cause of the error.

4.3. Practical result

Practical measures on a real installation showed with a data cycle of 2 ms a transmission error every 130 ms for 3 stations. The exact bit error rate can only be estimated, as we do not know the exact number of erroneous bits causing the erroneous frame. If we assume just one erroneous bit for one erroneous frame we can estimate a bit error rate of about P = $5\ 10^{-3}$, what results with Figure 4 to an undetected error T every 15 hours. In the practical installation there was reported an unexpected behaviour of the machine once every day.

The ProfiTrace – like other tools of this type – provides statistical information about the cycle time, the number of user bytes in the cyclic data transmission and has counters for erroneous frames, retries and sync frames. What is missing is the interpretation of these results. What is the potential risk if we have a certain number of retries? Is this quality of the installation now good, acceptable or should the installation be improved?

It depends on the number and probability of undetected errors which are acceptable by the end user. The time between undetected errors may be estimated by the

$$T_E = \frac{T_C}{R(P)} \quad (6)$$

with the assumption, that there is only one error in one frame. This is probable the case for a small P. The size of R(P) may be estimated with

$$R(p) \cong 10^{4 \cdot \log(P)+K} \quad (7)$$

where K is graphically estimated to be in the range of 2 to 6 . K depends on the number of user data in the frame. With K=4 we get a medium value for Profibus frames with a length of about 30 user bytes. This approximation is plotted in Figure 11.

To get this feature it is possible to develop for the ProfiTrace tool a plugin which does these calculations. The number max value of retries, sync and erroneous frames during a measurement time is taken. If the number is smaller than 10^{-2} it is assumed, that there is only one error for each frame and P is calculated based on the length of the frame and R(P) is estimated with the approximation formula to get a fast result. The relation with the cycle time gives the expected time interval between two not detected transmission errors. In practical installations the exact figures are not of interest. It is important to know that if there are retransmissions in a Profibus installation more than ten in a second (with top bit rate of 12 Mbit/s), there will be undetected transmission errors in an installation with a daily appearance. This indication can be calculated and displayed to the end user of the installation.

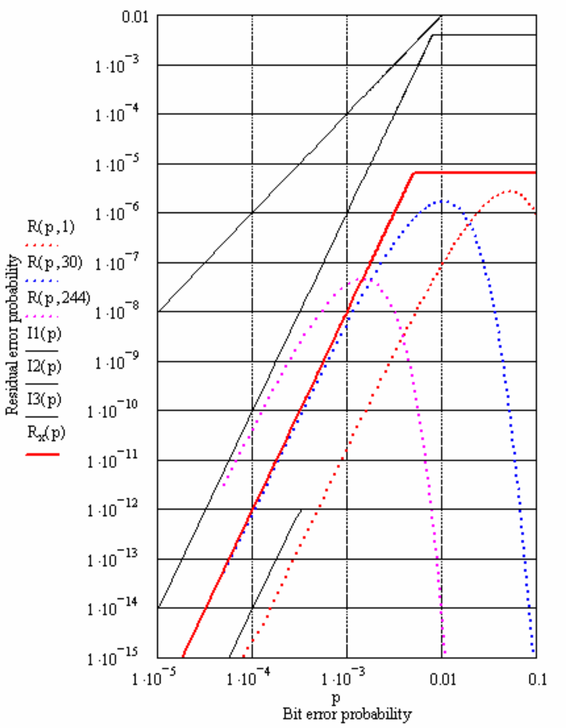

Figure 10: Approximation of relation R with P

In practice there is no problem to get a network with zero repetitions for several hours with an installation following the installation rules. In such a network there is no risk of undetected transmission errors for several years!

5. Conclusion

Bad installations and terminations may not be visible in the normal control: the error detection and correction mechanism of Profibus does hide the problem from the application. No errors in the application does not mean no errors in the transmission. If there are transmission errors, there is a statistical probability that there will be one or the other transmission error passing undetected to the application.

There exist today simple monitoring tools like the ProfiTrace, which allow the statistical analyse of transmission errors in a Profibus network. Here we propose "zero tolerance". Only if there are no transmission errors in a network for e.g. one hour, there is no risk of undetected errors for several years. We showed how a plug-in to this tool may estimate based on different relations and mechanisms for error detection the probability of undetected transmission errors. We recommend to check the installation at the commissioning and to repeat these measurements on a regular maintenance phase e.g. every year.

In more than 80% of all cases where there are problems with a Profibus installation in the industrial application the reasons are the cabling, the correct shielding and grounding and the cable terminations. A simple tool to localise the source of errors is a simple oscilloscope triggered by a bus monitoring tool.

If these simple rules are followed, Profibus-DP is a high quality network.

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