HOW TO ASSESS RELIABILITY OF INDUSTRIAL WIRELESS SOLUTIONS

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Abstract: Wireless communication is an emerging technology for industrial automation applications. Many solutions are available which more or less consider industrial related requirements. One of the main concerns of industrial automation system users is the reliability of wireless communication. The subject of this paper is a method to assess reliability of wireless communication from the point of view of industrial automation applications. Characteristic parameters are introduced which can be used in analytical studies, in network simulations or measurements to assess reliability with respect to intended industrial control processes. In particular the different use cases for the characteristic parameters are stated as well as the stochastic nature of these parameters. Finally the influences are mentioned which have to be taken into account while assessing wireless industrial communication systems.

1 INTRODUCTION

Wireless communication technologies are widely spread in daily life. The price of wireless products is thereby the main design aspect with respect to the consumer market. Reliability is one of the minor design goals. Therefore, almost everyone has had negative experiences with such technologies and has developed concerns regarding the usage of wireless in industrial communication.

Indeed a number of measures are applied to make industrial fit products from cheap solutions of the consumer market (Dzung, 2005), (Weczerek, 2005), (Siemens, 2007). However, how can users be convinced that wireless solutions meet the requested reliability of industrial automation applications?

This paper starts with a definition of reliability with respect to the application area - industrial automation. Thereafter a model is introduced from which relevant characteristic parameters are derived which are used to assess reliability. Some examples follow which show how to assess wireless solutions with the described approach.

2 MODEL

2.1 Requirements

First we would like to clarify what reliability means in context of wireless industrial communication. A user of an industrial communication system expects a certain process value, e.g. position or temperature, at a certain interface within a defined time frame without any errors under defined conditions. This is an informal definition. In order to be able to assess the degree of fulfilment of this requirement by means of simulation or measurement, a formal model is required.

First of all this model has to take into account the application field - the industrial automation. The parameters to be investigated have to be in line with the design criteria of industrial automation systems. Parameters such as Data Throughput or Bit Error Rate are normally not useful to design a particular automation application which e.g. shall manufacture a product in a certain time frame or with a certain cycle.

Furthermore, the model has to consider that there is no general wireless standard available for industrial automation which fits to all communication tasks. Several different technologies are used for industrial automation. A unified interface between communication and application is

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not available. Therefore the model has to be independent of a certain wireless technology and even more it has to be open for future developments in wireless communication such as Ultra-Wideband.

Last but not least the model should represent the conditions of reality as accurate and complete as possible and necessary. The following section introduces an approach which fulfils the mentioned requirements.

2.2 Approach

The abstraction of a distributed automation application using wireless communication is shown in Figure 1. Wireless communication modules are seen as an internal or external part of automation devices. The automation devices have to fulfil certain functions in a distributed automation system and for that they have to communicate in our case using a wireless communication media. From the point of view of the automation system, the communication characteristics at the interface provided by the wireless solution are important. These communication characteristics have to fit to the time and error categories used in the industrial automation area as introduced later in this document.

It must be clearly defined as to what the communication interface is, upon which the characteristics are related to. This interface consists of a hardware part such as Ethernet or Dual Ported RAM and a software part such as a communication protocol or a driver. Besides a clear statement concerning the communication interface and the communication characteristics, the conditions have to be described under which the characteristic values are valid. The conditions can be described by a number of influencing values which have different origins. It is obvious that the communication system itself affects the characteristics concerning e.g. topology or data rate. It is also evident that the communication media has influence because of other users of the spectrum or because of the effects of multi path fading. Furthermore, the characteristics depend on the options chosen in the devices, which means on its configuration. It is sometimes forgotten that also the application affects the characteristic values in the sense of the size of a packet or the cycle of requests on the communication system.

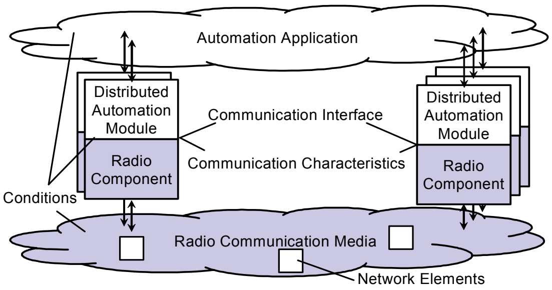

Figure 1: Model approach for the assessment of wireless industrial communication systems.

2.3 Characteristic and Influencing Parameters

The analysis of literature concerning the usage of characteristic parameters to describe and assess communication behaviour has shown that there are remarkable differences. Moreover, the definitions come mostly from the application field of Ethernet, Internet or telecommunication which does not fit to the application field of industrial automation (e.g. in (DIN EN 61491, 1999), (DIN EN 61209, 200)). That is why it was necessary to find appropriate definitions. The following characteristic parameters are proposed to assess wireless communication systems with respect to industrial automation applications:

- Transmission delay
- Response time
- Update time
- Data throughput
- Packet loss rate
- Residual error rate
- Activation time after energy saving mode
- Energy requirements

It has to be mentioned that it is not required nor recommended to use all parameters at the same time to characterise a communication solution for a certain application. The following sections show exemplary which parameters fit to which kind of use cases. The definitions of the listed characteristic parameters can be found in (VDI/VDE 2185, 2007).

It is obvious that the values of the characteristics are influenced by several parameters. That is why it is important to know these parameters and their values. Some of the parameters can be set with certain values but it is also possible that the parameters can not be influenced. In this case it is important to determine the value of the parameter to be able to assess the determined characteristic value.

The first set of influencing values is related to the application. This includes

- A background communication load, which exists in addition to the communication under investigation
- A user data length (packet size)
- A distance between the radio components
- An application period
- A relative moving speed between the radio components
- A relative moving direction between the radio components

The second set of influencing values is related to the radio technology and the radio devices. It includes

- A topology
- A frequency band
- A security functionality
- A safety functionality
- A type, direction and gain of antenna
- A transmission power
- A data rate via the physical media
- A media access control method
- A retry limit in case of errors
- A data rate at the communication interface
- A communication cycle

The third set of influencing values is related to the environment in which the communication will take place. It includes

- An application area
- Electromagnetic disturber
- Other frequency users
- Environmental conditions

Taking into account the listed influencing parameters while determining target-oriented relevant characteristic parameters, these can be used to assess the time and error behaviour of a wireless communication solution with respect to automation applications.

2.4 Use on Reliability Definition

Now we can define the term reliability more specific and we can describe how to assess reliability. In line with the definition of chapter 2.1, reliability can be seen as the degree in which you can expect that a wireless communication solution meets the limits of relevant characteristic parameters. With this definition it is obvious that the assessment of reliability needs stochastic measures. The characteristic parameters are random variables. Their behaviour follow probability density functions. The reliability is the probability that a value of a characteristic parameter is less or equal to the limit defined by the automation application.

3 ASSESSMENT OF RELIABILITY

3.1 Event Driven Data Transmission

Event driven data transmission is relevant for process variables which indicate that a certain state is assumed. For example when a work piece reaches a specified position that it can be machined or when a fluid reaches a defined level in a tank. In these cases it is of interest as to how long it takes to transfer the information from sensor to the control unit e.g. programmable control logic (PLC). The appropriate characteristic parameter to assess the behaviour of a communication system is the transmission delay.

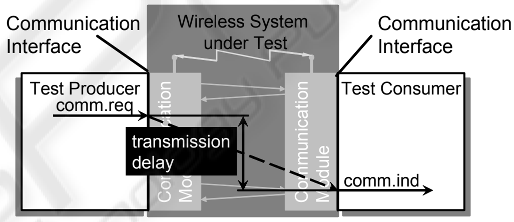

Figure 2: Definition of the transmission delay.

The definition of the transmission delay is based on a producer consumer model (see Figure 2). It is the time duration from the beginning of the handing over of the first user data byte of a packet at the communication interface in the test producer, up to the handing over of the last user data byte of the same packet at the communication interface at the test consumer. It may be necessary to transmit several telegrams between the communication modules e.g. for acknowledgment. Furthermore, network elements such as base stations may be involved in the communication producing additional delays. All these delays are covered by the transmission delay.

As already mentioned, the characteristic parameters and therefore the transmission delay are random variables. Next it is shown which parts of the transmission are randomly distributed and which are constant. Furthermore, it is shown which parts are specific for wireless transmission and what makes these special considerations necessary.

To get a deeper understanding of enlarged transmission delays, the most important segments of a transmission delay value are listed in Table 1.

Table 1: Time segments which influence the transmission delay value.

Time Segments		Remark
Latency of application interface	T_{ai}	The data transfer between application module and communication module may influence the transmission delay value remarkably.
Latency of implemen-tation	T_i	The implementation of the communication module influences the transmission delay value remarkably.
User data length	L_{ud}	The user data length is related to the data which is generated or consumed by the automation application.
Data rate	Bd_{ud}	This rate is the radio transmission rate of the user data. Sometimes a symbol rate is given. In this case a symbol may consist of more than one bit. The header of a packet containing the user data may be transmitted with another data rate.
Technology constant	T_{tc}	The technology constant contains all technology relevant protocol overheads which are the same for each transmission such as fixed idle times or the time to transmit headers or tails.
Technology variable	T_{tv}	The technology variable contains all technology relevant protocol overheads which may vary for different transmissions such as the time to get a clear channel or the back-off time. Depending on the technology, acknowledgments are required to complete a transmission.
Number of retries	N_r	If a transmission is disturbed, the packet is usually retransmitted. This may be possible at different layers.
Transmission deadline	DL	In some cases the transmission is terminated when a deadline is exceeded.
Time allocation of additional connections	Tac	If there is more than one connection established, the time allocated to the other connections within the same system has to be taken into account.
Global time slot	T_{GTS}	In systems with TDMA the maximum transmission delay can be calculated considering the global time slot.

The random nature of the transmission delay is being caused by the latency of the application interface and implementation, by the technology variable, the number of retries and the time allocation for additional connections. In contrast to wired communication, the wireless transmission is affected much more by environmental influences. Therefore, the random behaviour of the technology variable together with the number of retries and the time allocation for additional connections may influence the transmission delay remarkably

Taking into account the time segments listed in Table 1, the dependency of the transmission delay can be described in different ways. The first way is the given formula (1) and is illustrated in Figure 3.

$$T_{td} = f\left(T_{ai}(p), T_i(p), T_{ai}(c), T_i(c), L_{ud}, Bd_{ud}, T_{tc}, T_{tv}, N_r, T_{ac}\right) \quad (1)$$

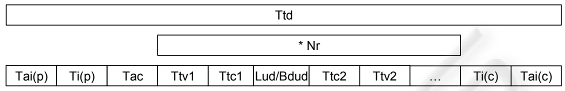

Figure 3: Time segments of transmission delay depending on re-transmissions, data rate and data length.

The second way to describe the transmission is given in formula (2) and Figure 4. The maximum transmission delay is fundamentally influenced by the maximum allowed deadline which covers the random behaviour of the media related time segments.

$$T_{tdmax} = f(T_{ai}(p), T_i(p), T_{ai}(c), T_i(c), DL) \quad (2)$$

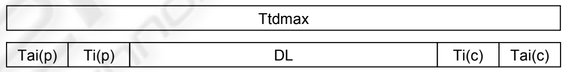

Figure 4: Time segments of transmission delay depending on a transmission deadline.

The third way to describe the transmission delay is given in formula (3) and shown in Figure 5. The maximum transmission delay is fundamental depending on the number of retries and the global time slot.

$$T_{tdmax} = f(T_{ai}(p), T_i(p), T_{ai}(c), T_i(c), N_r, T_{GTS}) \quad (3)$$

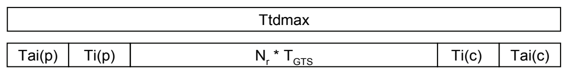

Figure 5: Time segments of transmission delay depending on a global time slot.

As an example typical results of transmission delay measurements are depicted in Figure 6. The lower part of the figure shows the number of packets, relative to the sample size, with certain transmission delay values. The above described random nature of the transmission delay can be observed. The reasons for the different values are mainly transmission retries because of disturbances and delays due to an occupied media. The curve follows a Beta probability density function.

The probability distribution function of the measurement is depicted in the upper part of Figure 6. It shows how many packets are transmitted by a certain point of time.

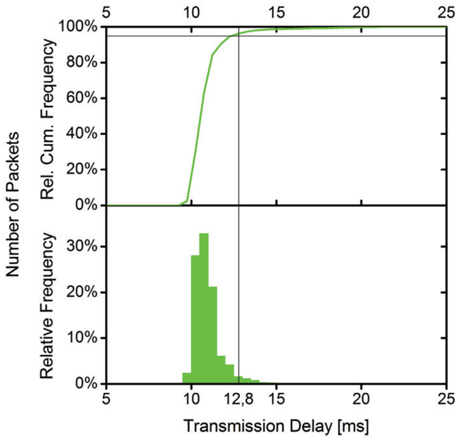

Figure 6: Probability Density Function and Probability Distribution Function (Cumulative Density Function) of packets' transmission delay.

To assess the time behaviour of a wireless solution, the well known statistical parameters for the centre (e.g. mean value) and for the variation (e.g. standard deviation) can be used. Our experience is that the 95th percentile value P95 is the best indicator for relevant changes in the time behaviour e.g. because of disturbances. It is a trade off between a feasible sample size (e.g. one million packets) and an adequate significance.

The maximum value is not qualified for assessment since it is a single value of a series of measurements and it is not sure that the real maximum value is captured. An infinite measurement of the transmission delay would be necessary or an inference to a larger population using methods of interferential statistics. However, the maximum value is considered so far as it influences the value of the 95th percentile P95.

The assessment of the reliability of an event driven data transmission means a comparison of a limit for a statistical parameter given by the application with the statistical parameters of a measurement.

3.2 Cyclic Data Transmission

Most of the control processes in industrial automation are cyclic. A process image is taken cyclically via input devices or process interfaces. It is processed by a controller and the result is output via output devices or interfaces. One example is the control of an overhead monorail system. The position is acquired cyclically and as a result the control information is transferred to the drive.

Also for these cases it is of interest as to how long it takes to transfer data e.g. from the position sensor to the controller. However, using the transmission delay to assess the time behaviour could be misleading. The problem is that in these cases different cyclic processes are involved which are not synchronised. Taking as an example a rotary encoder sensor in which the communication buffer is cyclically updated with the position information which is cyclically transferred to a controller. The effect of the asynchronism is shown in Figure 7.

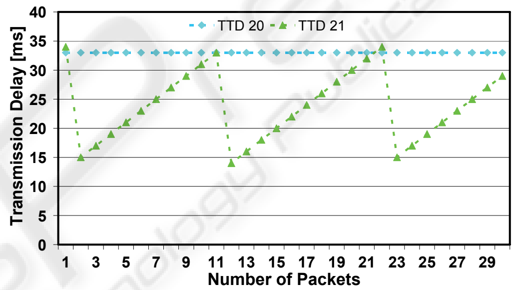

Figure 7: Effect of asynchronous cyclic processes on transmission delay.

Depending on the initial situation and the period of the cyclic processes, the transmission delay may have very different statistical parameters. In the case TDD20, the communication cycle is an integral multiple of the update time and therefore the transmission delay value is constant. In the case TDD21, first the transmission has been started just before the buffer update (maximum value) and next the transmission starts just after the buffer update (minimum value). Thus, the mean value may decrease even when the communication cycle increases as shown in Table 2. The variation on the other hand becomes much higher.

Since this behaviour is random and in reality more than two cyclic processes are involved, it is possible that the influence on the wireless transmission is overlaid by the effect shown in Figure 7 and can therefore possibly not be assessed. This behaviour must at least be considered.

In most cases the update time is the appropriate characteristic parameter to assess the time behaviour of communication systems with cyclic data transfer. The update time is ascertained according to the producer-consumer-model (see Figure 8). This means the period of time is from the delivery of a packets` last user data byte, from the communication interface of a consumer to the application, until the delivery of the last user data byte of the following packet of the same producer. Therefore the update time is at least as long as the transmission delay between producer and consumer, prolonged by the time of the application update within the producer.

Table 2: Transmission delay values for different communication cycles.

	TTD20	TTD21
Buffer update	40 ms	40 ms
Communication cycle	20 ms	21 ms
$N_r*(T_{tc}+T_{tv}+L_{ud}/Bd_{ud})$	13 ms	13 ms
Transmission Delay (Mean Value)	33 ms	23,8 ms

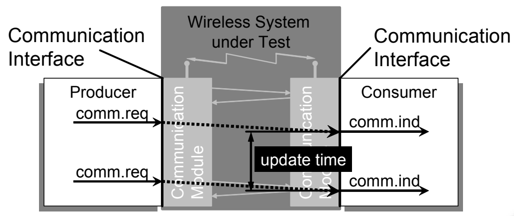

Figure 8: Definition of cycle time at producer-consumer model.

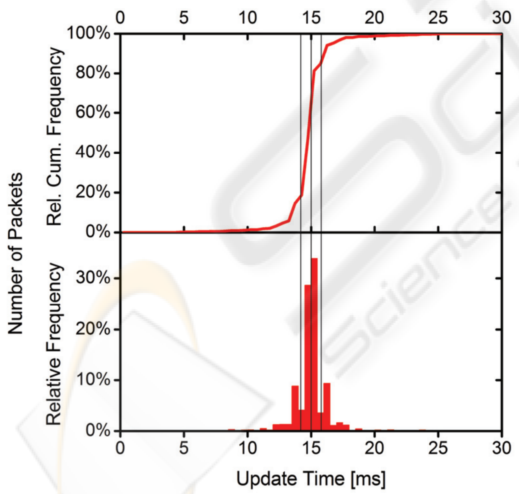

Figure 9: Probability Density Function and Probability Distribution Function (Cumulative Density Function) of packets' update time.

As an example typical graphs are depicted in Figure 9 for the probability function and the distribution function of packets with certain update time values. The update time is a Gaussian distributed random value. The mean value indicates in the first place the usability of the wireless communication system for a certain cyclic control process. Another important parameter is the span in the automation area known as jitter. However, it has to be mentioned that the measured minimum and maximum values which are used to calculate the span are most likely not the absolute extreme values. Again an infinite measurement of the update time would be necessary or an inference to a larger population using methods of interferential statistics. Therefore the span can only be assumed with a certain probability.

Furthermore, measurements have shown that the standard deviation value is well suited in order to indicate influences on the wireless communication system. Therefore, this parameter together with the span can be used to assess the reliability of cyclic data transmissions. The mean value follows the application cycle if the system is correctly configured. This means it is equal to the application cycle which is the period e.g. a sensor value is updated in the communication buffer.

3.3 Assessment of Error Behaviour

Up to now it was assumed that none of the transferred data got lost. That means the configured number of re-transmissions were sufficient to transfer the user data successfully. This chapter discusses how the reliability is assessed using the Packet Loss Rate (PLR).

The packet loss rate (PLR) is ascertained according to the producer-consumer-model. It reveals how many of the packets, transferred from the application to the communication interface within the producer, are transmitted from the communication interface to the application within the consumer. The packet loss rate is determined as follows:

$$PLR = \frac{N_{tx} - N_{rx}}{N_{tx}} \quad (4)$$

Where N_{tx} means number of transmitted packets and N_{rx} means number of received packets.

In principle industrial wireless communication solutions are designed to cope with the special environmental conditions. They are considered robust against interferer and industrial propagation conditions. Therefore, in principle no packets disappear. However, tacking into account the maximum limits of the transmission delay the situation changes. A remarkable packet loss rate can be noticed in the case where a packet is considered to be lost when a certain value of transmission delay is exceeded (or a deadline is missed). The calculation of the packet loss rate for a certain use case can be done as shown in formula (5). The number of packets is acquired, which have transmission delay values less or equal to the limit defined by the use case. The difference to the sample size is assumed to be lost packets. Thus, the packet loss rate is calculated with respect to use case specific limit of transmission delay. Especially interferers cause higher PLR values. Considering the packet losses and the transmission delay, the reliability can be assessed by comparing the PLR_{UC} with the required packet loss rate of the use case. Since also the PLR_{UC} is a random value, measures should be foreseen by the application for the case that data is not received within the expected time frame.

$$PLR_{UC} = \frac{N_{tx} - N_{rx}(t \mid t_{TD} \leq T_{TD\max_{UC}})}{N_{tx}} \qquad (5)$$

In the following chapter some examples are given on how the reliability can be assessed.

4 EXAMPLES

4.1 Overview

The examples presented in this chapter shall illustrate how the characteristic parameters are used for certain purposes. The measurement scenarios, the results and their assessment are not the topic of this paper.

The results presented in this chapter come from measurements with an IEEE 802.11g based industrial communication solution. Different influences have been investigated. A test system generated packets with a length of 64 octets and transferred them with an application cycle of 15 ms to the interface of the test producer. At the test consumer, the packets are transferred to the test system. The test system measured the values of the characteristic parameters. In none of the presented cases could a packet loss concerning (4) be investigated.

The systems under investigation are not specified in detail in the current document since the project in which the measurements are made has not yet been completed. Moreover, in this paper the method of assessment is in the focus and not the absolute results of the tests.

4.2 Assessment of Event Driven Data Transmission

The following figures show the number of packets which are received after a certain time in line with the above given definition of transmission delay. Figure 10 shows the result of a measurement with an industrial wireless solution made in an absorber hall that means without any environmental influences.

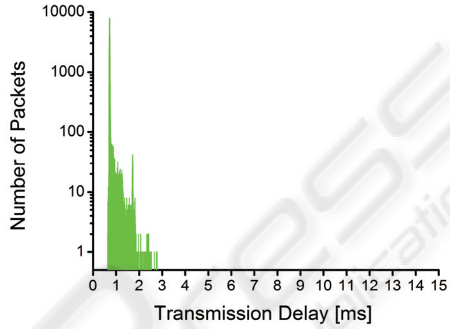

Figure 10: Histogram of transmission delay in absorber hall.

In Figure 11 the same system was placed in a factory hall. Influences due to the environment can be ascertained.

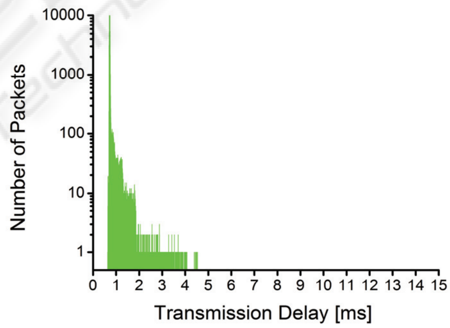

Figure 11: Histogram of transmission delay in factory hall.

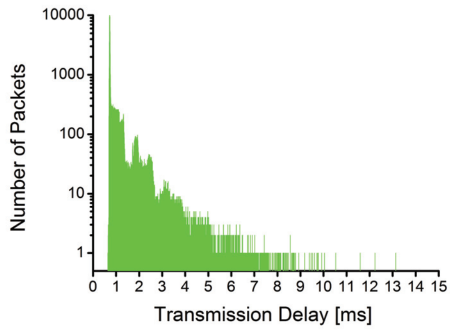

Figure 12: Histogram of transmission delay in factory hall with interferer.

In Figure 12 an interferer was finally activated and a considerable influence can be ascertained.

However, comparing the values in Table 3 with a transmission delay limit e.g. of a high speed I/O system which is 10 ms, it is obvious that the reliability of the communication is comparable for all investigated conditions. In particular there was no packet loss concerning the definition of formula (5). That means even when the wireless communication is noticeably influenced, this does not mean that the requirements of a certain application can not be fulfilled.

Table 3: Transmission Delay Values.

Transmission Delay [ms]	Min.	Max.	P95
Absorber Hall	0,6	2,8	0,8
Factory Hall	0,6	4,5	0,8
Interferer	0,7	13,1	2,0

4.3 Assessment of Cyclic Data Transmission

Figure 13 to Figure 15 show the update time for the same scenarios described in the previous section.

As shown in Table 4 the mean values of the update times are equal to the application cycle of 15 ms for all scenarios. By contrast the span differs. Taking a limit for the span from ±1,5 ms in the first case the requirement is fulfilled. In the second case 614 packets and in the third case 12.563 packets are out of range. This results in a reliability of 99,9% and 97,4% concerning the definition of this paper.

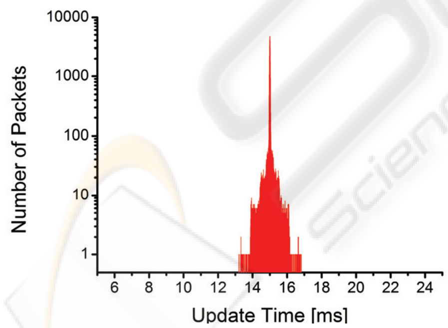

Figure 13: Histogram of update time in absorber hall.

Table 4: Update Time Values.

Update Time [ms]	Min.	Max.	Mean
Absorber Hall	13,2	16,8	15,0
Factory Hall	11,2	18,8	15,0
Interferer	7,0	23,0	15,0

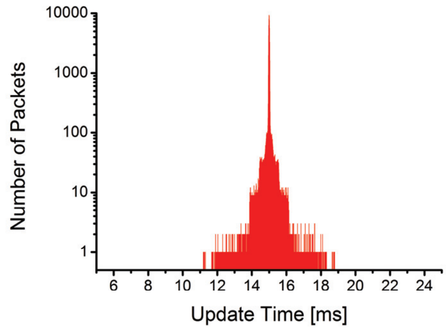

Figure 14: Histogram of update time in factory hall.

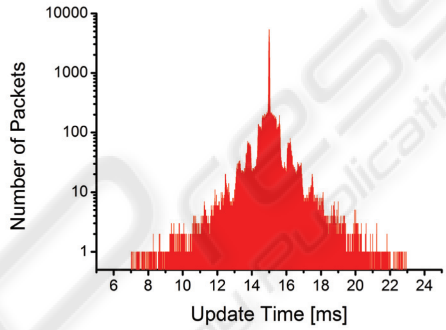

Figure 15: Histogram of update time in factory hall with interferer.

5 CONCLUSIONS

In the paper we presented a proposal on how to assess the reliability of industrial wireless solutions. A fundamental requirement for such a method is the focus on industrial automation applications. That is why characteristic values such as transmission delay, update time and packet loss are used in the way defined in this paper. It was pointed out that these parameters are random variables which mean the statistical parameters have to be considered.

The described method has been used to assess the coexistence of different industrial wireless communication solutions. Furthermore, these solutions are currently being used to assess the possibility of using wireless communication in automation applications with safety requirements. A test system is available which supports the measurements of the described characteristic parameters (Rauchhaupt, 2006).

The approach can be used for analytical studies, simulations and tests. The method is required for wireless communication since the dimension of influences can be remarkably greater than in wired systems.

The work described in this paper is accompanied by important manufacturers of automation and radio solutions, and users of such systems which work together in the German Society of Measurement and Automation. As a result the characteristic parameters presented in the paper are introduced in the VDI/VDE-Guideline 2185 "Radio based communication in industrial automation".

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