IMPACT OF DIFFERENT BIT RATES ON PERFORMANCE CHARACTERISTICS OF INDUSTRIAL WLAN SOLUTIONS

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Keywords: Communication Systems, Performance Analysis, Reliability Analysis, Transmission Characteristics.

Abstract: Wireless communication is already widely used in industrial automation applications. Many solutions are available which consider industrial related requirements more or less. Thus, reliability and performance with respect to the specific requirements are the main concerns of industrial automation system users. Some of the wireless solutions base on the well-known Wireless LAN. The development of IEEE 802.11 was driven by the demand on highest possible data rates e.g. for video streaming applications. This paper proves whether the increased bit rates are appropriate to the requirements of industrial automation applications. A test methodology is introduced which can be used to get the necessary characteristic parameters with respect to the application field - industrial automation. The impact of bit rates on packet loss probability and therefore on the performance is analysed. Together with the transmission time for a successful transmission with one attempt a cost function has been developed. It shows for WLAN solutions, that the highest bit rate is not adequate to meet the reliability and performance requirements of industrial automation applications.

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.

Also the most popular wireless communication technology WLAN, which uses the probabilistic media access control CSMA/CA, has disadvantages concerning time behaviour and reliability of packet transmissions. With setting up the bit rate the end-user has to find a trade-off between transmission time and loss probability of transmitted packets. Following the common sense the user takes a high bit rate for fast transmissions or a low bit rate for a high reliability of communication.

In this paper a test methodology is described which allows the investigation of wireless solutions with respect to industrial automation application requirements and conditions. This approach is used to define appropriate test conditions and to set-up a test system in order to investigate the influence of different bit rates on performance and reliability.

The transmission time is measured and the number of retransmission is investigated. Furthermore the loss probability is derived from the number of retransmission. Finally, a cost function has been developed in order to provide a guideline to find an appropriate trade-off between performance and reliability.

The paper is structured as follows. In chapter 2 the test methodology is presented and the main important influencing parameters are discussed and its values are defined. In chapter 3 the characteristic values are introduced which have been used for the investigations and the test system and its components are explained. The test results are discussed in chapter 4. The cost function is derived in chapter 5 and the conclusions out of it are presented in chapter 6.

2 TEST METHODOLOGY AND CONDITIONS

Because of the special requirements and conditions of industrial automation applications a test methodology has been developed by the authors (see Rauchhaupt, L., Krätzig, M., 2008.). It considers the

Schimschar A. and Rauchhaupt L. (2010).
IMPACT OF DIFFERENT BIT RATES ON PERFORMANCE CHARACTERISTICS OF INDUSTRIAL WLAN SOLUTIONS.
In *Proceedings of the 7th International Conference on Informatics in Control, Automation and Robotics*, pages 387-394
DOI: 10.5220/0002942203870394

application field, but is independent of a certain wireless technology. All relevant influencing parameters are taken into account (see Gnad, A., Krätzig, M., Rauchhaupt, L., Trikaliotis, S., 2008). These parameters are configured well-directed or if not possible documented. Here only the main important influencing parameters are described because of the limited space.

The focus lies on the impact of different bit rates on the performance and reliability of WLAN solutions. For WLAN systems according to IEEE 802.11 this is related implicitly to the physical layer coding and modulation schemes as discussed later on.

Although the WLAN implementation (hardware and software) has a noticeable influence on the time behaviour (see e.g. Rauchhaupt, L., Krätzig, M., 2008, Rauchhaupt, L., 2009) it is not considered here. However, an industrial WLAN solution was selected which provides the best performances in terms of jitter of the transmission time (i.e. span) and in terms of minimum outliers which means in number and in value.

Also interferences of other wireless systems are not considered. They are well investigated as described e.g. in ZVEI, 2009.

Thus, a simple point-to-point topology is used for the investigations consisting of a WLAN access point and one client. The attenuation between the two devices was 60 dB which is according to about 10 m line of sight. The WLAN channel 1 (2412 MHz) was chosen.

The test packets have been generated by the client. They had a user data length of 64 octets which is the minimum length for an Ethernet packet and a typical length in Ethernet based automation applications.

In previous investigations the dependency of the performance from the value of the transmit time interval became obvious. Therefore in these tests the client generated the test packets with a random transmit time interval between 15 ms and 25 ms. The random generation is based upon a uniform distribution function.

The sample size of each test case was 30,000 packet transmissions which resulted in test durations of about 10 minutes.

NOTE: With the chosen implementation a bit rate of 5.5 MBit/s was not adjustable. When this bit rate has been configured the WLAN system showed the same behaviour as for automatic bit rate control mode. Therefore, the bit rate 5.5 MBit/s is not considered here.

3 CHARACTERISTIC PARAMETERS AND TEST SYSTEM

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 (EN 61491, 1999), (EN 61209, 200)).

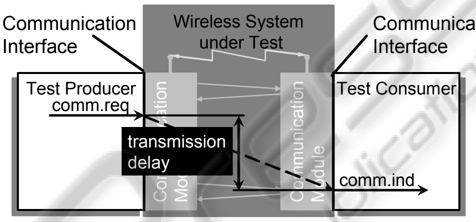

Figure 1: Definition of the transmission delay.

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 time
- Update time
- Response 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 definitions of the listed characteristic parameters can be found in (VDI/VDE 2185, 2007).

In this paper we focus on the transmission time. It is related to event driven applications. For example when a work piece reaches a certain position in order to 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 of a communication system to assess its behaviour is the transmission time.

The definition of transmission time is based on a producer consumer model as shown in Figure 1. 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 time.

In order to assess the reliability the retry rate is analysed. It is defined as the number of WLAN packets that are necessary to transmit the content of one generated test packet.

The system under test implements a widely used radio technology - Wireless LAN and its application interface is very common - Ethernet. Therefore, standard measurement equipment can be used to implement the above mentioned test methodology.

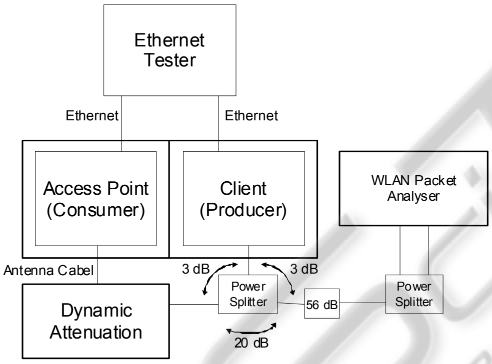

Figure 2: Test architecture.

The test architecture is shown in Figure 2. The devices under test (WLAN client and WLAN access point) are put into separate radio proof enclosures. The test boxes achieve an attenuation of 90 dB against the outer environment. The radio interfaces of access point and client are connected by an antenna cable. It is led via a power splitter and a dynamically changeable attenuator. This approach excludes interferences to the radio communication.

The dynamic attenuation has been configured to a constant value of 57 dB. Together with the attenuation of splitter and antenna cable the total attenuation is 60 dB as specified for the test cases. Besides the relevance of this value for automation applications it has been shown that in this way the transmit signal is low enough to avoid an overmodulation and high enough to be unaltered. The second output of the power splitter is connected to another static attenuation of 56 dB in order to connect a WLAN packet analyser. A second power splitter is used in order to provide the signals to two channels of the WLAN packet analyser. This increases the reliability of the packet monitoring. The total attenuation between client and WLAN analyser is 62 dB. The total attenuation between access point and analyser is more than 133 dB. Thus the analyser captures only the packets transmitted by the client.

The test packets are generated by an Ethernet tester which transfers the data to the WLAN client. As mentioned before the user data length is 64 octets. The generated packets are compliant to PROFINET-IO telegrams. The advantage is the specific frame type and content which simplifies the identification of packets during analysis.

The packets transferred by the WLAN client are monitored by WLAN analyser. If the packets are successfully received by the WLAN access point they are transferred to the Ethernet tester and are monitored there also.

During analysis in a first step the user data packets are filtered out of the packets monitored by the WLAN analyser. Since every user data packet can be identified by a unique payload it can be found within the user data packets monitored by the WLAN analyser. If a user data packet is listed more than ones it means retries has been initiated by the WLAN client because of missing acknowledgements. This way the retry rate can be calculated.

In addition a timestamp is included within the user data. With help of this timestamp the Ethernet tester is able to calculate the transmission time for every successfully received packet.

4 TEST RESULTS

4.1 Transmission Delay

The measured transmission time consists of random and constant components (see also Rauchhaupt, L., Krätzig, M., 2008.). Examples for constant components are the frame spacing times or the signal propagation delay on the wireless medium. These components have the same values in every measurement of a sample. The random nature of the transmission time is being caused by latency of application interface and implementation, by the technology variable, the number of packet retries and the time allocation for additional connections.

Therefore, stochastic methods are required in order to analyse the measurement results. Statistic parameters such as mean value, median, standard deviation, 95%-percentile (p95), maximum and minimum value of a test case can be analysed.

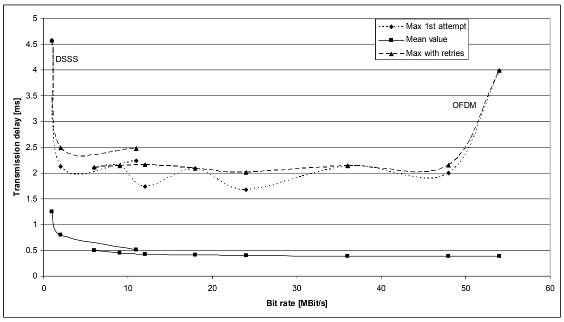

Figure 3: Transmission time for first attempt and including all retries.

In Figure 3 then mean value of the transmission time including all packets retries is depicted. Furthermore the maximum transmission time values out of all value which are received after the first attempt is shown as well as the maximum transmission time values of all successfully received packets.

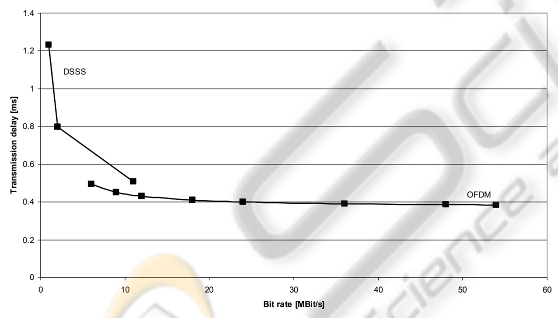

Figure 4: Delay for transmissions without retries.

The first result is that the maximum values for a certain bit rate are almost the same independent how often a packet is retransmitted. Since there is no contention on the medium it can be concluded that the maximum values of the transmission time are determined in the first line by the implementation including interfaces from and to Ethernet.

The second result is that the value of the outliers increases dramatically for 54 Mbit/s, while the mean value is similar to all other bit rates.

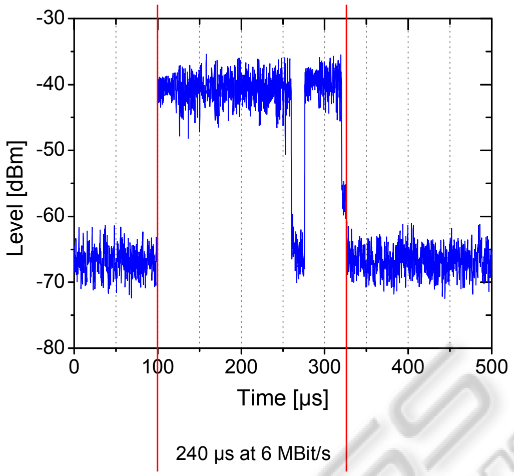

Figure 5: Medium utilisation time at 6 Mbit/s.

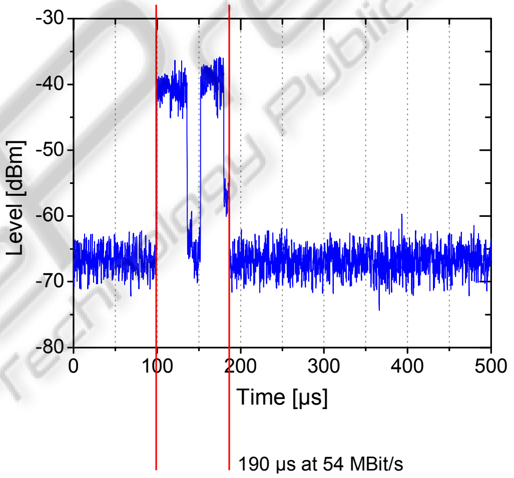

Figure 6: Medium utilisation time at 54 Mbit/s.

Since the influence of the number of retransmissions is not very significant in Figure 4 only the mean values of the transmission time are depicted for those packets which are received at the first transmission attempt.

The diagram shows that at low bit rates the differences between the neighbouring values are high. The differences become smaller with higher bit rates. However, from 12 Mbit/s on the increase of the mean values is very low. The reason for that behaviour is the time for a packet on the medium.

Figure 5and Figure 6 show the signal power level of a WLAN data packet and an acknowledge frame during transmission on the medium. It can be seen that the increase of the bit rate by 9 (from 6 Mbit/s to 54 Mbit/s) causes only a decrease of the medium utilisation time by about 1.3 (from 240 µs to 190 µs). The reason is that because of the backward compatibility of the WLAN standard parts of a packet are transferred with 1 Mbit/s or 2 Mbit/s. With 64 octets user data only this aspect has remarkable influence on the transmission time.

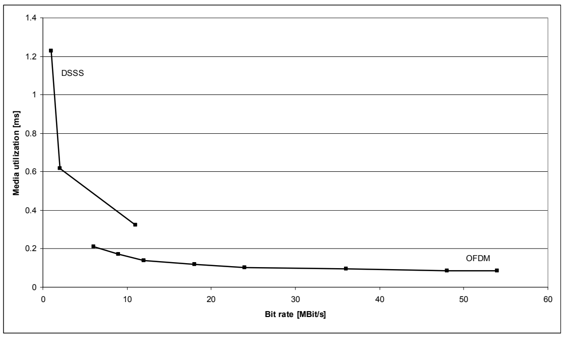

Figure 7: Media utilization time for different bit rates.

Figure 7 illustrates the medium utilisation time over the bit rate. As shown in Figure 5and Figure 6 the medium utilisation time is defined as time duration from the beginning of a data packet transmission up to the end of the related acknowledgement. Retransmissions are not considered. The curves in Figure 4 and Figure 7 show a similar characteristic. This underlines the influence of the medium utilisation time on the transmission time.

In addition the curves in Figure 7 indicate also another effect. The WLAN standard IEEE 802.11 specifies different coding and modulation schemes as listed in Table 1.

Table 1: Overview of the transmission method and modulation for each data rate.

Data rate	Method	Modulation
1 MBit/s	DSSS	DBPSK
2 MBit/s	DSSS	DQPSK
5.5 MBit/s	DSSS	DQPSK
6 MBit/s	OFDM	BPSK
9 MBit/s	OFDM	BPSK
11 MBit/s	DSSS	DQPSK
12 MBit/s	OFDM	QPSK
18 MBit/s	OFDM	QPSK
24 MBit/s	OFDM	16 QAM
36 MBit/s	OFDM	16 QAM
48 MBit/s	OFDM	64 QAM
54 MBit/s	OFDM	64 QAM

Theses schemes are related to the configurable bit rates. In particular the coding scheme Direct Sequence Spread Spectrum (DSSS) and Orthogonal Frequency Division Multiplex (OFDM) have different impacts on the medium utilisation time. Therefore, the curves are separated for theses coding schemes in Figure 3, Figure 4 and Figure 7.

4.2 Number of Retransmissions

The bar chart in Figure 8 depicts the number of packet transmissions needed for a correct reception by the access point. A logarithmic scale is chosen for the number of transmissions in order to see the small number of retransmissions. The interesting fact of this picture is that while using bit rates related to DSSS coding the maximum number of retransmission is one. Obviously this coding scheme is more robust than OFDM.

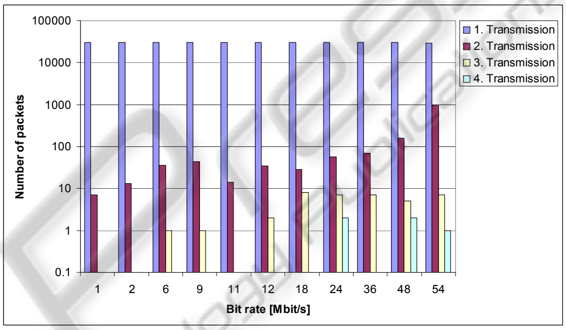

Figure 8: Number of packet retransmissions over bit rate.

For all bit rates related to DSSS the entire number one retransmission is about ten. In test cases with bit rates related to OFDM coding a number of packet transmissions with at least two retransmissions can be noticed. Especially for higher bit rates also up to four retransmissions can be seen.

The diagram in Figure 9 illustrates the total number of PROFINET-IO packet transmissions sent by the WLAN client via the medium. This means the transmission of all data packets including all retransmissions. Figure 9 shows almost constant values for DSSS bit rates. They are concentrated next to the lower limit of 30000 packets. The OFDM bit rates do not have such a constant behaviour. However, for low OFDM bit rates only little differences exist. At higher bit rates the number of packet transmission increases. Especially for 54 Mbit/s the number of required transmission is remarkable high. For this bit rate 31000 WLAN packets are required to transmit 30000 Ethernet packets. This results in a retry overhead of about 3.3 percent.

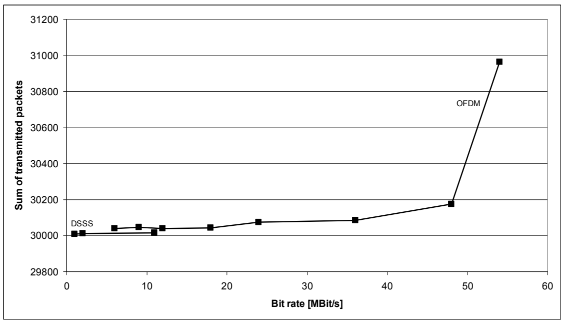

Figure 9: Total number of packet transmissions.

4.3 Loss Probability

Based on the discussion of retransmissions the loss probability shall be determined. Out of the results shown in Figure 8 a geometric distribution is assumed. The geometric distribution deals with the number of independent trials required for a single success. A famous example of this distribution is tossing a coin until it lands on heads.

The formula given in equation 1 describes the expectation value E(X) of required transmissions for each bit rate. Whereas N is the sample size, i is the indicator of the transmission attempt and k_i is the frequency of an attempt within a test case.

$$E(X)=\frac{1}{N}\cdot\sum_{i=1}^{n}k_i\cdot i \tag{1}$$

N in formula 1 has not been calculated as shown in equation 2 since the sample size is well known for the test cases.

$$N=\sum_{i=1}^{n}k_i \tag{2}$$

The estimation of the success probability p of a packet transmission is equivalent to the reciprocal of the expectation value E(X) of required transmissions (Formula 3).

$$\hat{p}=\frac{1}{E(X)} \tag{3}$$

With the well-known equation 4 it is easy to get the loss probability out of the success probability.

$$\hat{q}=1-\hat{p} \tag{4}$$

Figure 10 illustrates the loss probability for different bit rates, which has been calculated with the last-mentioned equations. In this picture we differentiate again between DSSS and OFDM method. The diagram is similar to the one of Figure 9. The only difference is the normalised ordinate. Additionally, the figure presents low loss probabilities for DSSS bit rates. On the other hand values for OFDM bit rates are essentially higher. However, for a wide range the values are almost constant. Furthermore, the abovementioned extreme value at 54 MBit/s exists also in this figure. In summary the diagram underlines the results concerning the robustness of DSSS coding scheme. OFDM bit rates are not recommended with respect to a robust communication.

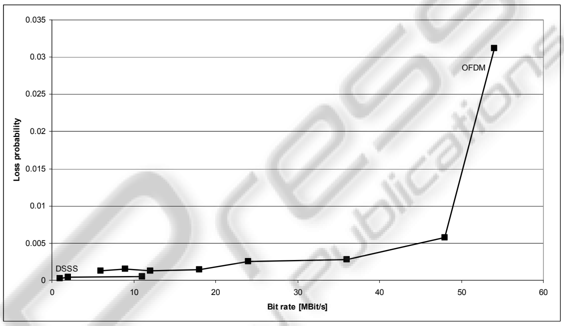

Figure 10: Loss probability for different data rates.

5 COST FUNCTION

In order to consider all the above mentioned aspects for the assessment of a wireless system a cost function has been developed. It is a trade of between (a high) transmission time and (a low) loss probability. Therefore the values of the transmission time measured in section 4.1 and the loss probability values calculated in section 4.3 are used. For further discussions the cost function shall depend on the bit rate. In addition the values should not have a dimension unit.

Therefore, the mean values of the transmission time for packets without retransmissions are used. Thus the influence of retransmissions on the time behaviour is avoided. In order to get values free of dimension units the transmission time values are put in a ratio to the shortest transmission time mean value. This value belongs to a bit rate of 54 MBit/s. Thus the value of bit rate 54 MBit/s is assigned to the ratio of one in the cost function. All other bit rates have values greater than one. The ratio for 1 MBit/s is the highest and is almost three times greater than for the reference bit rate.

The second part of the cost function is the loss probability. It is multiplied by the transmission time ratio. The complete formula is given in equation 5.

$$C(DR) = \frac{\overline{t_{TD1}(DR)}}{t_{TD1}(54MBit/s)} \cdot \hat{q}(DR) \qquad (5)$$

The cost for different bit rates is illustrated in the diagram of Figure 11.

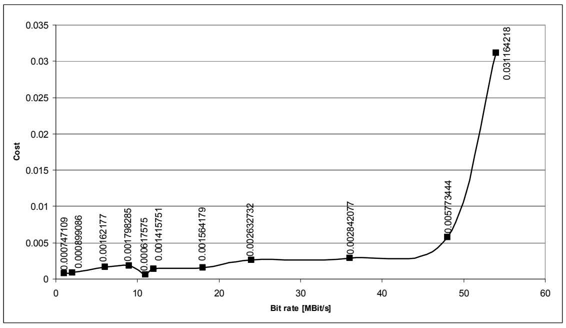

Figure 11: Cost function of WLAN packet transmissions.

The diagram shows a general trend. The cost values increase with higher bit rates. This means better communication behaviour can be expected with lower bit rates.

Taking a deeper look to the cost function the minimum is visible at 11 MBit/s. As in the figures before this diagram also offers the maximum at 54 MBit/s.

Bit rates lower than 24 MBit/s are almost in the same range of values. However, there is no constant increasing of cost values with higher bit rates. At bit rates greater or equal than 24 MBit/s the trend of the cost function rises noticeably.

6 CONCLUSIONS

The focus of this paper was the investigation of the influence of bit rates on the reliability and performance of WLAN systems with respect to industrial automation applications. Thus the test setup and the values of the influencing parameters reflect the communication requirements of this application field.

A first result of the measurements is the confirmation of the generally way of thinking. Higher bit rates cause shorter transmission time values. On the contrary lower bit rates cause less packet retransmissions. However, in the context of industrial automation a more detailed look at the results is necessary.

Thus there is an important finding, that there are differences between the coding schemes DSSS and OFDM. Obviously DSSS shows a more robust behaviour than OFDM. DSSS is included in IEEE 802.11 b. In contrast IEEE 802.11 g uses OFDM in favour. However, in order to be compatible with IEEE 802.11 b devices IEEE 802.11 g also supports bit rates using DSSS. With this background the user can choose DSSS for more reliable connections or OFDM for faster transmissions.

Another result is that the maximum values of the transmission time are more influenced by the implementation than by the number of retransmissions. Thus optimisation potential of the WLAN implementation can be detected using the presented test approach. In fact there are remarkable differences between industrial WLAN solutions as investigated by the authors in other tests projects.

However, also the retransmissions play an important role when a congested medium is taken into account what was excluded in the given investigations.

Therefore a cost function was introduced that opens the possibility to consider transmission time and required retransmissions for a successful communication. It can help to find the appropriate trade-off between a fast and a reliable wireless connection. As shown in Figure 11 a transmission with 11 MBit/s has the lowest cost value and is therewith the best trade-off with respect to considered application field. Also other bit rates of the IEEE 802.11 b specification, which uses DSSS and the corresponding modulations, showed an appropriate behaviour. The worst behaviour offer transmissions with 54 MBit/s. This fact disagrees with the popular opinion that a high bit rate is the best solution real-time automation applications. In addition the investigations show that even the medium utilisation with 54 Mbit/s is the highest because of the retransmissions. This is an important outcome with respect to the required efficient spectrum use in order to support coexistence between wireless systems.

Other interesting points of the explained measurements are the lower costs of 12 Mbit/s and 18 MBit/s in comparison to 6 Mbit/s and 9 Mbit/s. The rates of 24 Mbit/s and 36 MBit/s are also acceptable.

As a conclusion the best bit rates for industrial automation applications are the ones of the IEEE 802.11 b specification. With the focus on fast transmissions bit rates between 12 Mbit/s and 36 MBit/s could be chosen. The bit rates 6 Mbit/s, 9 Mbit/s, 48 Mbit/s and 54 MBit/s should be avoided.

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