Coexistence considerations for wireless CAN systems with safety-requirements

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This paper discusses considerations regarding wireless coexistence and wireless system density when CAN traffic is transferred via wireless links. Wireless application communication requirements of safety-related crane applications are presented using CANopen and CANopen Safety in industrial environments. A methodology will be introduced for assessing coexistence of wireless CAN applications with today used wireless industrial networks and with future systems e.g. conform to EN 300 328 V1.8.1. Test specification and test implementation issues are highlighted. Furthermore, exemplary test results are presented that show the potentials and advantages of a systematic, application oriented test approach. Finally, further work is proposed and future requirements and guidance of international guidelines and standards is addressed.

Application communication Requirements

Wireless connections to mobile machines or movable machine parts are the logical consequence of distributed control. Thus, it is not surprising that data traffic of controller area networks (CAN) is also transmitted wirelessly. However, the requirements e.g. of crane applications are challenging because of safety-related controlling.

Figure 1: Electric Overhead Traveling cranes (Photo DEMAG)

Electric Overhead Traveling cranes (EOT cranes), as shown in Figure 1, are often controlled by the operator via cable-bound pendants or - with increasing tendency - via wireless remote control devices.

The electrical controls of hoists and cranes have traditionally been and are still today realized in certain markets and in highly robust applications in the form of traditional contactor controls. Increasing complexity in the scope of functions (e.g. tandem crane functions) as well as increased demands on the functional safety of industrial cranes and crane components, promote the spread of processor controls, ideally using a safe serial field bus (e.g. CAN Open Safety) to connect the different controls of a crane between each other.

Against this background, EOT cranes represent `spatially sprawling machines`, where the transmission of the control signals generally could be realized via classic control lines (e.g. trailing cable systems), or alternatively over the `air` by radio. Wireless radio interfaces also offer manufacturers of industrial cranes considerable benefits in terms of variant management (fewer hardware variants) and process costs (e.g. reduced installation work).

Currently in discussion are automation concepts that focus on intensive information exchange between personal, production machinery, and produced objects in order to increase the efficiency and flexibility of production. This requires powerful, flexible, heterogeneous networks which include also CAN and its data transmission over wireless links.

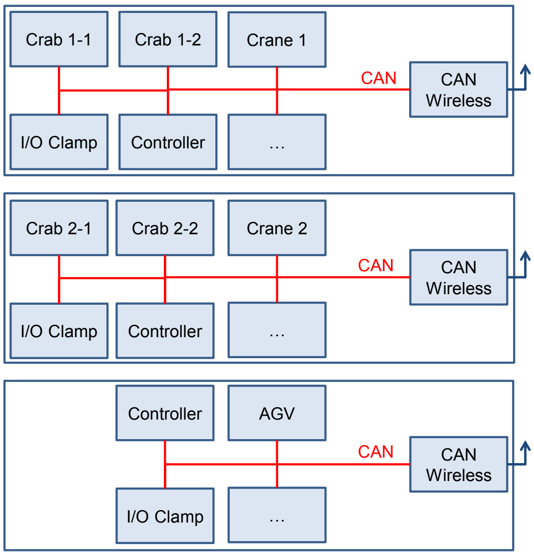

Figure 2: CAN Crane application scenario with wireless communication link

One imaginable scenario of these future concepts shall be depicted in Figure 2. It shows a block diagram with two cranes and one Automated Guided Vehicle (AGV). The equipment contains Controller Area Networks which connect the control devices. By wireless links the movement of cranes, its crabs and of the AGV is controlled corresponding to needs of the production process. Information can be exchanged between cranes, AGV and produced objects in order to guide the product through the production process corresponding to the product state and the transport resources. The product can request a crane to be loaded or unloaded, AGV and cranes can be synchronised or personal can be guided via terminals to take specific actions.

The required mobility and flexibility for these future application scenarios will increase significantly the number of wireless applications in industrial environments and consequently the density of wireless communication devices and systems. Therefore, a careful analysis of communication load and frequency spectrum use is of fundamental importance. The coexistence of all wireless applications is a prerequisite for the acceptance and success of wireless applications. Especially with regard to the requirements of EN 300 328 V1.8.1 that prefer adaptive medium access control and limits the spectrum use for other systems it is difficult almost impossible to assess coexistence and efficient medium use by many wireless devices and systems at a certain position.

In the following sections is explained how the coexistence between wireless communication devices and systems can be assessed based on tests in order to optimise wireless products and applications.

Wireless coexistence assessment

The first question to be answered was how to assess the density of wireless communication devices and systems. How can be measured whether the limit of devices or systems at a certain location is exceeded or not? For a start you can assume that the density is not exceeded as far as coexistence exists between wireless equipment. For device density it means internetwork coexistence. For system density it means coexistence between networks of the same type. However, also the coexistence to other wireless communication networks is of interest. In [1] coexistence or more precise wireless communication coexistence is defined as “state in which all wireless communication solutions of a plant using shared medium fulfill all their application communication requirements”. This definition makes clear that wireless coexistence cannot be assessed based on radio frequency parameters. Moreover, performance parameters have to be considered that can describe the application communication requirements. For safety-relevant automation and control applications the requirements are dominated by two main aspects:

1. The information shall not be corrupted so that the application runs in an unsafe state.
2. The availability of the application should not be degraded.

The CANopen Safety specification shall be used to meet the requirements of the first aspect. However, for an unreliable communication this may degrade the second aspect, the availability, especially when deadlines are exceeded.

Thus, our approach of wireless coexistence assessment is based on the determination of performance parameters.

In [2] we proposed parameters that characterises the time and error behaviour of wireless communication systems. As one example the transmission time is introduced here. Referring to Figure 3 the transmission time is the period of time from starting the delivery of the first user data (bit or octet) of a transmission to the observation interface of a producer (e.g. proximity sensor) until the delivery of the last user data of the same transmission from the observation interface of a consumer (e.g. programmable logic controller).

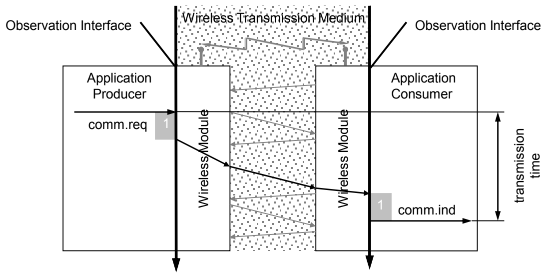

Figure 3: Transmission time definition

Other terms are used to characterise the duration of transmissions e.g. latency. However, exact definitions are mostly missing so comparisons are hardly possible.
The definitions of the transmission time can also be found in [3] together with the definitions of additional so called characteristic parameters such as update time, packet loss rate, etc. For the purpose of assessing safety relevant applications we also monitor the event of exceeded safeguard cycle time (SCT).

Assessment methods

Different approaches are possible to determine the values of the characteristic parameters for assessing the coexistence.
In an early stage of a product development simulations can be carried out. Therefore, communication models are required. If these models are available investigations with any number of devices and systems can be executed. However, the behaviour of the real products is not comprised. In addition it is difficult to take into account the radio propagation or the radio channel characteristic.
Therefore, another approach is the measurement with real products in the target application environment. The problem in this case is to place at disposal the required number of wireless communication devices and systems. Furthermore, the target environment is difficult to control. Moreover, it is almost impossible to carry out such investigations e.g. in a factory hall when a production process is running.
Therefore, we choose another approach - the test with special laboratory equipment.

Test procedure

A formal test procedure has been established in order to get significant, reproducible and comparable results.
First, a test plan is written. It represents the requirements specification of the test project. It contains a non-formal description of the test scenarios which are derived from the target application. The objective of the investigations is defined and the conditions and requirements to be considered from the application point of view are described. Therefore, we are using parameters that influence the performance of a wireless product, the so called influencing parameters. These parameters describe the application communication requirements (e.g. number of devices), the characteristic and the configuration of the wireless communication product (e.g. transmission power), and the environmental conditions (e.g. other wireless communication systems). For details see [4]. The test plan describes also the system under test, the characteristic parameters and its limits.
Next a test specification is developed. It identifies in detail the test cases. The document is required by the test person who is carrying out the test. Therefore, it specifies all required detailed information in order to implement, configure, and set-up test system and system under test and to carry out the tests. First the experimental setup is depicted. This includes the architecture and the interfaces between test system and system under test. Furthermore, the configuration of system under test is described. Next it is explained how the characteristic values are determined. This includes, which data is measured and how it is measured as well as how the characteristic values are calculated.

Finally, the test cases are specified in detail. For it the influencing values are summarised and classified in order to form test groups and test cases.

Test example

This section briefly introduces an example of a test scenario for assessing the coexistence capability of a control system that transmits CANopen and CANopen Safety data using a wireless link. The objective was to assess the system density and the coexistence with other wireless communication systems.

Table 1: Example of CAN data traffic that shall be transmitted via a wireless link

Node ID	Service	Time
31	PDO2 (rx)	43.6
32	PDO2 (rx)	46.3
1	SRDO	60.3
1	SRDO	60.8
31	PDO1 (rx)	63.9
11	NMT-EC	64.5
32	PDO1 (tx)	68.4
11	SRDO	79.0
11	SRDO	79.7
21	SRDO	80.1
21	SRDO	80.6
31	PDO2 (tx)	86.8
32	PDO2 (tx)	90.5
13	SRDO	93.0
13	SRDO	93,6
1	PDO1 (tx)	94,5
31	PDO2 (rx)	95,2
32	PDO2 (rx)	96,5
32	PDO1 (tx)	100,2

The application scenario of one system is similar to that shown in Figure 2.
In the test plan the number of wireless control systems that shall operate simultaneously was specified and the wireless communication system that operates in the same area. The distances between the devices of a system and between the systems, the communication load and other influencing parameters were derived from the target application scenarios.
In Table 1 an extract of the CAN traffic is listed. It gives an impression of a target communication load. Besides of process data objects (PDO) also safety-relevant data object (SRDO) and others shall be transmitted via the wireless links.
Based on these requirements of the target application scenarios the test specification was developed. Thus the test project is structured in test suites, test groups and test cases. The example in Figure 4 shows the structure of a test suite. Before entering in investigations of specific influence, reference test are carried out. Here the basic functionality of one system under test is analysed in order to implement an optimal test-setup. This is necessary to get significant series of measurement that are not influenced by the test equipment. The difference of test group TG 1 and TG 2 is the implementation concept of the wireless communication system. In test group TG 3 the optimal implementation is tested while Wireless LAN systems operating in parallel in the same frequency area.

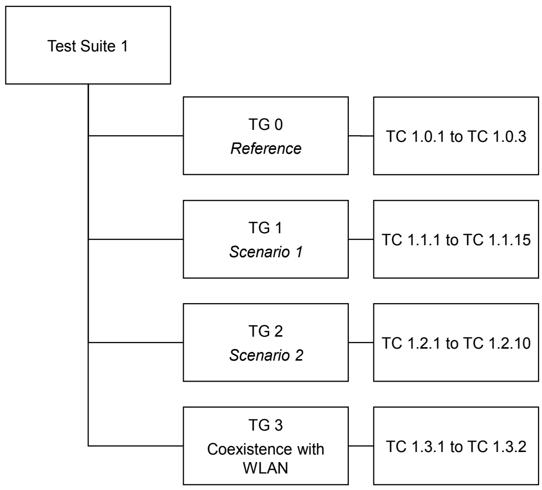

Figure 4: Test suite overview

Table 2 lists the defining, influencing parameters of the test cases TC 1 to TC 15 of test group TG 1. These are the number of systems under test (# system), the number of additional wireless systems of the same type (VSG), and the size and type of communication load within the CAN networks. Details of the number of wireless communication systems, the used frequency channels, the medium utilisation, the transmission power etc. are recorded in the test specification document.

This applies also to the specification of the number and type of CANopen objects, its transmission intervals etc.

Table 2: Test case list

TC	# Systems	VSG	Communication load
1	1	-	Distributed communication request
2	1	1	Distr. comm. request
3	3	1	Distr. comm. request
4	1	-	Alternating, concentrated communication request
5	1	1	Altern. conc. comm. req.
6	3	1	Altern. conc. comm. req.
7	1	-	Concentrated communication request
8	1	1	Conc. comm. request
9	3	1	Conc. comm. request
10	1	-	Burst communication request
11	1	1	Burst comm. request
12	3	1	Burst comm. request
13	1	-	Worst case scenario
14	1	1	Worst case scenario
15	3	1	Worst case scenario

Based on the test specification the test system is implemented. Figure 5 depicts the application part of the test system. The devices A.n form one system under test. Thus, in this configuration three systems under test operating in parallel and are investigated.

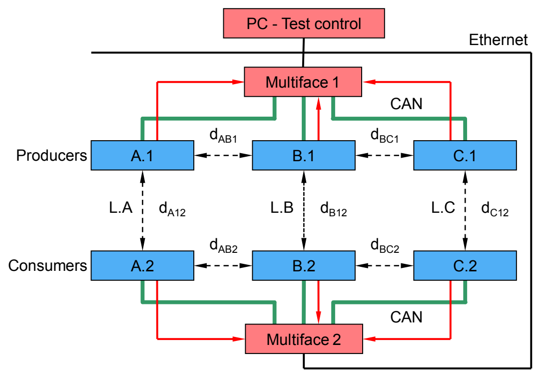

Figure 5: Test system implementation - application part

Each system under test uses one wireless link L.X. Furthermore, in Figure 5 the distances $d_{X.n}$ to be specified are illustrated.

A test control application, implemented on PC, is used to configure and control the test equipment with regard to the specified test cases. Furthermore, it controls the test process and collects the measurement results. Multiface is equipment that generates data traffic and measures the values of the characteristic parameters. Since the measurements include not only the transmission via the wireless medium but also the device behaviour the results allow the assessment from the application point of view. The measured values are transferred via Ethernet to the PC for post-processing and analysis.
The wireless part of the test system is shown in Figure 6. In fact, it is not wireless and therefore called radio frequency (RF) part. The wireless devices are placed in RF shielded test boxes. These boxes are connected via coaxial cables. Programmable attenuators are used to implement the pass loss of the transmission signal due to the distances between the devices. Thus, the distances between the devices of one system under test as well as the distances between the devices of different systems under test are implemented.

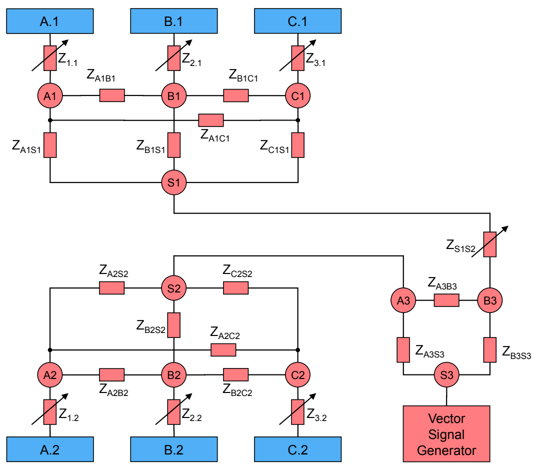

Figure 6: Test system implementation - RF part

Furthermore, a Vector Signal Generator (VSG) is connected to the test system. It is used to emulate additional wireless systems. Therefore, models are developed that represent the use of the radio medium concerning time, frequency and power. Thus high system density can be emulated and the effect on the systems under test investigated.

If you connect in addition a Spectrum Analyser to the RF network you will get a picture as shown in Figure 7. The abscissa represents the frequency spectrum of interest, the ordinate the time scale. The signal power is characterised by different colours. Red, yellow, green and light blue indicate noticeable signal strengths. That means in case of wireless communication signals a wireless packet is transmitted.

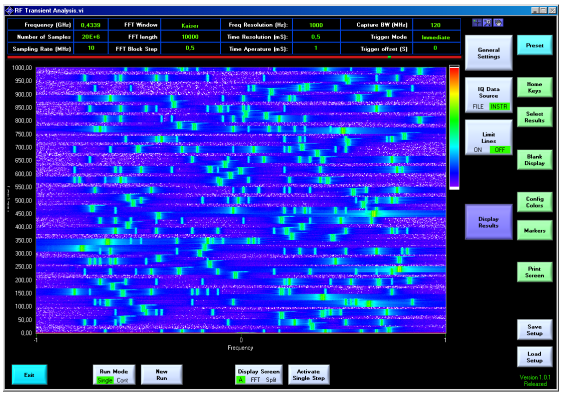

Figure 7: Spectrogram of 10 emulated and 3 real wireless frequency hopping systems with different distances between devices and systems

Figure 7 shows a situation where three systems under test and 10 systems emulated by VSG are using the spectrum. All wireless systems implemented a frequency hopping mechanism. That means a frequency channel is used only for a short period of time. Then it is switched to another frequency channel. This technique is advantageous especially in industrial environments, where the radio channel is time variant and frequency selective.
This example shows the approach of investigating the coexistence of wireless communication systems in a laboratory. So, the essential influences can be analysed under deterministic and reproducible conditions. However, it is reasonable to carry out the same test cases (or a part of it) in an industrial-like environment in order to experience the relevance of the influence of the radio propagation conditions to the results measured in laboratory.

Analysis of test result

As mentioned in previous sections application oriented characteristic parameters are used to assess the coexistence.

In this paper we will focus mainly on the transmission time.

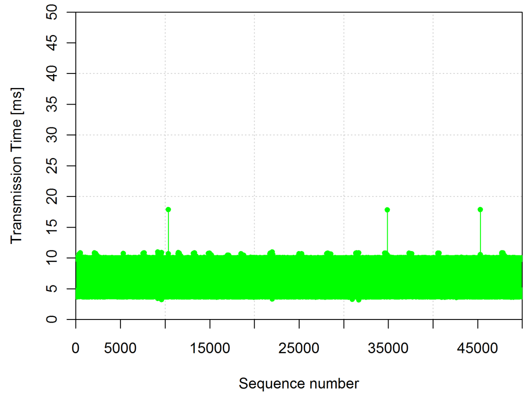

Figure 8: Timeline of transmission time

Figure 8 shows the transmission time values of all packets of one test case. Since the sample size is 50.000 this picture gives just an impression of the time behaviour. It can be seen that there is a range between about 4 ms and 11 ms. This means the transmission time varies by about 100%. An in depth analysis of the behaviour can be done by focussing to the time values of a few consecutive packets. For the coexistence assessment the three spikes in Figure 8 are of interest. Do these time values exceed the application communication requirements or not. Usually such single spikes do not cause problems for the application as far as the general time behaviour meets the requirements.

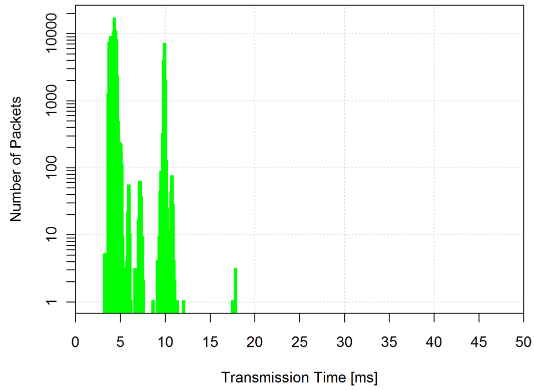

Figure 9: Histogram of transmission time

For further analyses we generate a histogram of the transmission time values as depicted in Figure 9. It illustrates the number of packets that belong to a range of time values. It has to be mentioned that the scale of the ordinate is logarithmical. Thus also smaller occurrences of time values are visible.

In Figure 9 mainly two maxima can be noticed.
The variation around the maxima can have different reasons:

1. The RF frontend does not suit to industrial automation applications.
2. The wireless medium access mechanism waits for a free medium.
3. Cyclic processes are not synchronised (medium access mechanism, operating system, and application software).
4. The software design is suboptimal.

The second maximum indicates that for some packets one retransmission was necessary in order to successfully transmit the CANopen data. In few cases additional retransmissions were required. Again, in principle also for safety relevant applications this does no matter as far as the safeguard cycle time is not harmed.

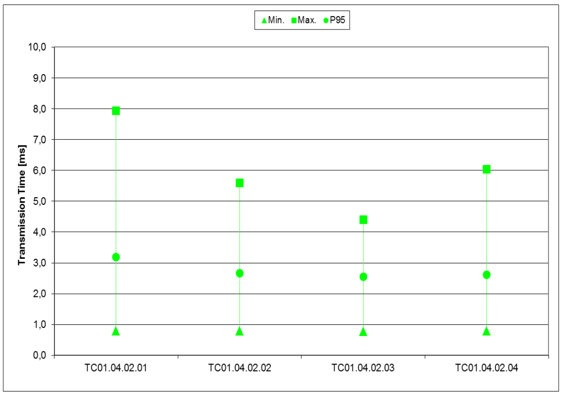

Figure 10:Transmission time summary

Figure 10 gives an example, how the transmission time changes depending on conditions of different test cases. For comparison three statistical parameters of the transmission time are used: the minimum, maximum, and percentile p95 value of the samples. The maximum and percentile p95 value indicate the degree of influence at different system density. Thus, a tendency concerning the coexistence state can be provided on which a valid risk analysis is possible.
It has to be noted that the maximum values in Figure 10 are measured maxima of the given samples. The absolute maximum, considering all possible retransmissions, the longest software delay, the maximum waiting time for a clear channel etc. is usually far above of the measured maximum. Therefore, this theoretical, absolute maximum is useless for assessing the coexistence.
In Figure 11 the histogram of the update time is depicted. The variation of the different delays that are produced by the medium transitions (CAN - Wireless - CAN) lead to a distribution of the time differences of arrival even at a constant transmission interval of 25 ms in the given case. However, local maxima are visible which point to a slotted medium access mechanism.

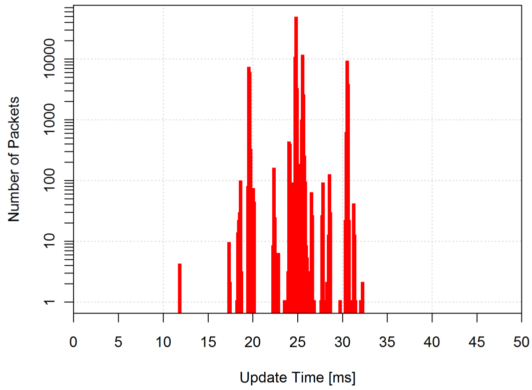

Figure 11:Histogram of update time

In cases of very high system densities violations of the safeguard cycle time (SCT) limit could be noticed.

Test conclusion

The analysis of the variation of the statistical parameters of characteristic values provides a solid fundament for assessing the achievable system density and the coexistence behaviour of a wireless communication system. The histograms of characteristic parameters such as transmission time or update time provide valuable information on the overall behaviour of the system under test. The time series analyses of the characteristic parameters give detailed knowledge about trends or periodic behaviour. Finally, the comparison of the values of the statistical parameters with the safeguard cycle time (SCT) and the number of occurrences of SCT violations are technically justified arguments to decide whether the wireless communication product is suitable for safety relevant applications or not.
It has been shown in many tests that system density and coexistence is not exclusively influenced by the challenges associated with the wireless link. Also the medium access mechanism and the medium utilisation of the system of interest and

the wireless communication systems that competing on the medium play an essential role. Therefore, attention shall be paid on the transmission and management of SRDO messages. Be aware of the relevant communication needs and avoid unneeded traffic. Just as important are implementation issues. This applies to hardware design, operating system, software design and implementation, buffer design etc.

Summary

This article introduced the support of wireless CAN device development based on methodological tests of the wireless communications time and error behaviour. This is especially important to insure availability of safety-related control and networking e.g. for crane applications. In this paper we focused on the problem of crowded spectrum in industrial environments. The presented approach shall be seen in the light of future development of application communication requirements. Future request on growing number of wireless CAN devices and systems are considered. Furthermore, additional wireless communication systems based e.g. on WLAN, Bluetooth, WirelessHART or other wireless technologies are taken into account.
The methodological approach provides resilient data about the coexistence capability and maximum system density. Thus, manufacturer of production systems can base their concepts on a reliable fundament. This is a way of creating confidence in the potential of wireless communication. However, it also shows clearly the limits concerning device and system density.
Furthermore, the approach is appropriate to optimise wireless products with respect to medium use and coexistence capability.
Further work concentrates on a wireless coexistence model in order to complement the tests by simulations. This permits early assessments even when devices are not available yet. One example is the influence of devices that are designed according to the new requirements of EN 300 328 V1.8.1 which will be mandatory from 2014.The test approach takes into account the standard tests for industrial wireless applications that have been developed in a research project. These standard tests are the fundament of a VDI guideline that is currently developed.

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