Methodology for holistic assessment of dependability in wireless automation

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***Abstract*—This paper is dedicated to the growing role of dependability assessment for wireless networks in industrial automation systems in particular with respect to future flexible production processes. First an overview is given over definitions of dependability and its parameters. Terms are classified in order to derive the key terms for wireless communication with respect to automation applications. Dependability parameters for assets of wireless communication are discussed. Relevant dependability parameters including an up state function (USF) is proposed. The USF can be used in order to assess the dependability of complex wireless automation applications independent of wireless technology. The use of the USF is demonstrated with exemplary measurements of a wireless LAN system.**

Keywords—dependability, industrial automation, wireless communication, performance assessment

I. Role of Dependability Assessment for Smart Manufacturing

Dependability is the "ability to perform as and when required" [1]. Dependability itself is not a parameter that can be measured or calculated. It is rather used as a collective term for time-related quality characteristics of an item.

In industrial automation applications, the facets of dependability play an important role. If requirements are violated, production losses, demolitions of expensive machines or equipment, or injuries or death of personal can be the consequences. Therefore, the determination of dependability parameters of device parts, devices, equipment, machines and systems used in automation applications is an important topic. Current activities focus on the extensive use of digitisation of assets and networking for so called smart manufacturing, in order to implement more flexible, costumer oriented, cost efficient production processes.

The determination of dependability parameters of hardware components, such as mean time between failures or the failure rate, is commonly used. Digital communication is assessed using bit error probability or packet loss rate. However, especially with the future development of flexible production scenarios these approaches will not be sufficient to guarantee the required dependability of complex production systems. In our paper we focus on the dependability assessment (DA) of current and future wireless communication systems (WCS). Following aspects have to be considered in order to implement a suitable system of assessing, monitoring and influencing dependability for WCS in complex production systems:

- The objective of DA within the life cycle has to be defined.
- The asset of DA has to be defined.
- Dependability parameters shall be related to the application and not only focused on the communication.
- Wireless industrial applications (WIA) are characterised by different requirements for dependability. Therefore, a holistic approach is required, considering all WIA within an area.
- Production processes will change very quickly and it is not efficient to try to guarantee the highest possible dependability for all wireless applications at the same time.

This paper focuses especially on DA for development of new wireless technologies e.g. according to IMT-2020.

The rest of this paper is organized as follows: Section 2 reviews definitions of dependability and its parameters from different areas. Section 3 discusses relevant assets and their functions as basis for dependability considerations. Dependability parameters for a logical link are described in Section 4. In section 5 an up state function is proposed for a holistic assessment of the dependability in wireless industrial applications (WA). It is used with exemplary measurements in section 6. Finally, section 7 concludes the paper with directions for future work.

II. Dependability Assessment for Industrial Wireless Networks

The study of standards for industrial automation and telecommunications has shown a remarkable number of different definitions for dependability, reliability and its parameters. Therefore, step one was to clarify what dependability is and how it can be assessed.

One point of view depicts dependability as a collective term and allocates different characteristics and parameters. According to [1] dependability means the "ability to perform as and when required." It is noted that dependability includes different aspects e.g. reliability and availability. Thus, [1] concludes "Dependability is used as a collective term for the time-related quality characteristics of an item." According to this definition it is important to distinguish between the terms dependability and reliability.

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Reliability is defined in [1] as "The ability to perform as required, without failure, for a given time interval, under given conditions". Even if this definition is similar to the definition of dependability, some aspects are not taken into account, e.g. availability, recoverability or quality of service.

The definition of reliability in [2] is equivalent to a packet ratio: "The amount of sent network layer packets successfully delivered to a given node within the time constraint required by the targeted service, divided by the total number of sent network layer packets."

In this paper we use the expression dependability as a collective term and reliability as one characteristic. During the research of dependability definitions, an overview as depicted in Fig. 1 was developed. It shows several levels of dependability related terms and provides a selection of relevant parameters. The general definitions of dependability are complemented by communication related terms in the lower part of the Fig. 1. A detailed description of the terms can be found in [3]. An exemplary subset is used in Section 4

Dependability	
Performance Characteristics	e.g. Availability Reliability Recoverability Quality of service
General dependability parameters	e.g. Up time Down time Operating time between failures Operating time to failure Restart time
General probabilistic variables	e.g Mean operating time to failure Mean up time Mean operating time between failures Mean down time
Dependability parameters of logical link	e.g. Transmission time throughput Number of lost messages Update time Number of correct received messages
Probabilistic variables of logical link	e.g. Residual Error Ratio Message Error Ratio Message Loss Ratio

Fig. 1. Overview of dependability parameters [condensed of 4]

Another aspect where different definitions can be found in literature is DA. In [4] the assessment of wireless sensor networks for industrial applications use general dependability parameters. In telecommunication often communication related dependability parameters such as throughput or packet loss ratio are applied [5]. In [6] the aspect of different assets of considerations is respected. There is unmistakable distinction between application and communication level. For studies on dedicated short range communication the choice of appropriate metrics for application and communication level were made.

The dependability evaluation of WirelessHART is examined in [7]. They focused on permanent failures. Conversely, our approach is regardless of the technology and we consider transient and permanent failures in one or more systems.

In our paper we follow the classification in Fig. 1. Based on that we develop a wireless technology independent and application related DA usable for complex inhomogeneous WIA. With respect to the definition of reliability in [1] four main topics are taken into account: the reference to a specific item or asset, the function of the asset, the operation conditions for the function and finally, the observation time in which the function is to be carried out.

Definitions and discussions of operation conditions of wireless communication can be found in [8] and [9].

III. Assets of Industrial Wireless Communication

The initial point of our considerations is the essential function of communication, the transmission of messages between locally distributed application functions of an IAS. The messages are transferred via a reference interface from an industrial application system to WCS. Therein, they travel from source to target and finally pass the reference interface from WCS to IAS. As shown in Fig. 2, the characteristic of a logical link depends on the communication functions implemented within source and target and the transmission medium.

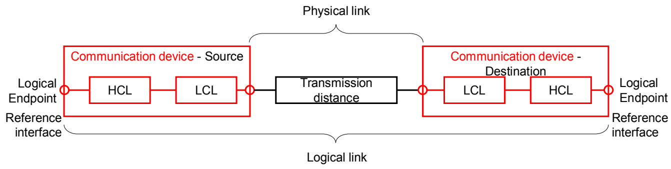

Fig. 2. Assets of wireless communication

In Fig. 2 the terms higher communication layer (HCL) and lower communication layer (LCL) are consciously chosen. Due to different wireless technologies and its implementations, it is hard to make consistent allocations, for example related to the OSI reference model. The implementations of the communication functions are mostly divided in higher and lower communication layers. They can contain different parts of the OSI reference model.

The behaviour of the WCS is described by characteristic parameters. The conditions which influence the behaviour of the WCS are determined by the communication requirements of the application, the properties of the communication system and the transmission conditions of the medium [9]. From the point of view of the automation application, the requirements on the time and error behaviour refer mostly to an end-to-end connection. However, there is no consistent definition what this connection considers. Therefore, we discuss the logical link as a relevant asset of wireless communication, because the logical link comprises communication devices. The physical link and the required function can be affected by different influencing factors in these assets. That can lead to communication errors like corrupted content, insertions or masquerade [10]. Additionally, an inadequate use of the communication by the application may lead to communication failures. The values of dependability parameters indicate communication errors. From the point of view of the application the correct reception of messages is of importance regardless of the amount of required transmission attempts. A message loss can be prevented with the help of protection mechanisms. Further relevant assets are the communication device, the physical link and the wireless communication system. These, and the function and the properties of the logical link are discussed more in detail in [11].

From application point of view we consider a WCS as a set of logical links (see Fig. 3). The message transmission is carried out by a set of wireless devices via a medium. Elements of the system can be one or more locally distributed automation components (Fig. 3). In the WCS the requirements of all logical links shall be ensured. The mutual impact between the logical links has to be considered in the WCS. In Fig. 3 the causes of errors which may occur are depicted.

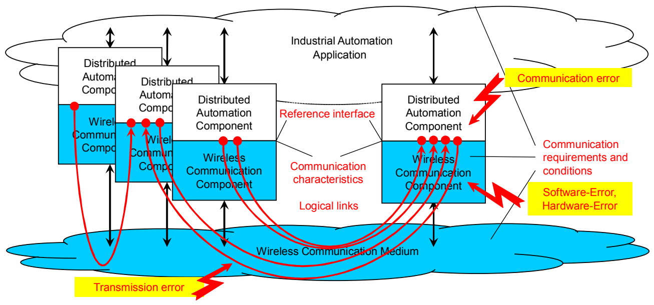

Fig. 3. Asset "communication system"

IV. Dependability Parameters Applied to the Logical Link

In this section an extract of dependability parameters with respect to wireless communication is presented. More details are given in [3] and [11]. At the beginning a definition from the International Electronical Vocabulary (IEV) is considered. This definition can be used to assess "the required function" of a logical link.

A. General dependability parameters

The up time is defined as a "time interval for which the item is in an up state" [1]. An up state is a "state of being able to perform as required" [1]. The required function of the logical link is to transmit message sequences from source to target. If this function is fulfilled the system is in the up state. Thus, to determine the up time, the messages have to be monitored. Theoretically, the up time starts with an explicit or implicit connection establishment and ends with a failure of the connection or with the disconnection due to an error. During an observation interval more than one up and down time interval is possible. Parameters to determine availability, recoverability, maintainability, safety and security are also of importance for a holistic discussion of dependability. With respect to the focus of this paper they are not further considered here.

B. Communication related dependability parameters

Additional parameters for DA of wireless communication are e.g. transmission time T_T, the update time T_U, data throughput (DT), message loss ratio (MLR), and number of consecutive message losses (CML). We refer to the definitions of T_T, T_U and DT in [12]. The number of consecutive message losses expresses how many messages in a row does not reach correctly the target application.

For each of the introduced dependability parameters limits shall be specified. However, it would be too strict to switch into down state, if one of the specified limits is exceeded for one message. Therefore, and in order to get a holistic and scalable dependability parameter for heterogeneous WIA, we propose an approach as described in the following section.

V. Holistic Assessment of Dependability

In section 4 various dependability parameters are introduced. The relevance of a parameter depends on the application and may be different for every logical link or for different WCS. For periodic control processes the update time is of major importance. However, the transmission time may also be of interest in order to monitor changes of communication conditions. For aperiodic processes, the influence of consecutive message losses may determine the event to transit to the down time. However, the disturbance of one logical link not necessarily leads to a failure of the WIA. A prioritisation of logical links and its characteristic parameters is proposed.

Taking the above discussed issues into account we propose the up state function Ψ(t) as a summarising parameter for DA of one or more WCS. We are considering the dependability parameters T_T, T_U, DT, MLR, and CML. These parameters are scaled to get σ_1 for T_T, σ_2 for T_U, σ_3 for DT, σ_4 for MLR, and σ_5 for CML. The general scale $||x||$ is given for each dependability parameter σ_i.

$$||x|| := \begin{cases} 1, & x \leq \alpha \\ 1 - \dfrac{x-\alpha}{\beta-\alpha}, & \alpha < x < \beta \\ 0, & x \geq \beta \end{cases} \qquad (2)$$

The scaling formula (2) is also valid for update time (σ_2), message loss ratio (σ_4) and number of consecutive message loss (σ_5). In the next step a weighting factor u_i for each dependability parameter $i = 1 \ldots n$ is introduced, with n as the number of different scaled dependability parameters. The up state function value ψ of a logical link can be calculated using equation (4).

$$\psi = \frac{1}{\sum u_i} \sum_{i=1}^{m} u_i \cdot \sigma_i \qquad (4)$$

For a WCS with j= $1 \ldots m$ logical links the up state value ψ is given by equation (5) considering a weighting factor v_j for each logical link.

$$\Psi = \frac{1}{\sum v_j} \sum_{j=1}^{n} v_j \cdot \psi_j \qquad (5)$$

Finally, the up state function Ψ(t) for $k = 1 \ldots p$ WCS and a weighting factor w_k for each WCS is given for the observation time interval $0 \leq t \leq t_{Ob}$ in equation (6).

$$\Psi(t) = \frac{1}{\sum w_k} \sum_{k=1}^{p} w_k \cdot \Psi(t)_k \qquad (6)$$

In Fig. 4 an example for an up state function is depicted. Depending on the calculation of the up state function value for each event, for normal operation the function will be located between the action limit and 1. If the action limit is passed, measures can be initiated in order to avoid passing the down state limit. Thus, critical situations and developments can be identified before the up state is left.

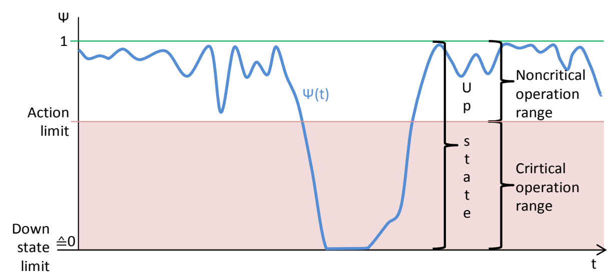

Fig. 4. Up state function

Summarized, if the system works, the function is in the range between 0 and 1. If a failure has occurred, the function has the value 0.

VI. Measurement Setup and Results

The measurement considers a WLAN network with one Access Point (AP) and three clients (CL). The WLAN network operates in the 2.4 GHz band on channel 7 with a channel bandwidth of 20 MHz. The Data Quality Analyser emulates the industrial application, generates the messages, captures the sent and the received messages and measures the time and error characteristics. The messages have a user data length of 64 Bytes and the content includes a time stamp and a sequence number. The transmission interval of message is 16 ms. Every CL is connected via the propagation effects replicator (PER) with the AP. The AP and each CL are located in different RF shielded boxes and are connected with the PER via coaxial cable. The PER emulate the radio channel between the radio devices. The distance between AP and each CL is 30 m. Effects like fading and shadowing are not emulated.

In Fig. 5 the weighted dependability parameters are shown as well as the USF from the logical link CL 2 and AP. It is shown for one logical link $n = 1$ and three dependability parameters $m = 3$. The T_T, the MLR and the CML is weighted, for a simple example with $u_i = 1$ and not pictured because $u_i = 0$ is T_U and DT. The limit for the weight of the separate dependability parameter is defined by the requirements. For example for the CML is the normed value $\sigma_5 = 1$ if the last message is received. If one message is lost $\sigma_5 = 2/3$ and if three or more lost $\sigma_5 = 0$. If a message is lost a transmission time does not exists, for that case or if the transmission time is over the limit (10^{-5}) the normed value for the transmission time $\sigma_1 = 0$.

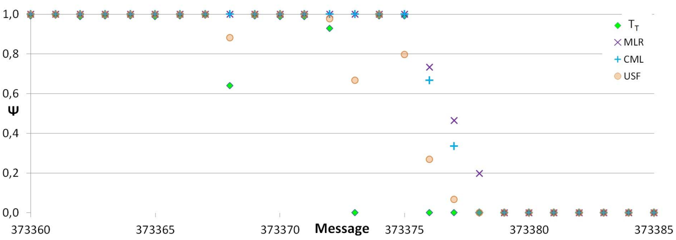

Fig. 5. Measurement results

The limits are defined for every logical link in the communication system according to the requirements. The aim of the USF is to expect the future behaviour like an indicator to intervene in case of online calculations if interferences occur. Fig. 5 presents the relation between the USF and the case of failure.

VII. Conclusion

With this paper we presented a methodology for holistic assessment of dependability of WCS with respect to IAS. The intention is the DA for all WCS in a production area independent of the technology. Dependability parameters refer always to a specific asset which has to be identified first. The types of dependability parameters used for assessment depend on the type of asset. If one and the same parameter is used for different assets the required values will most likely differ. Dependability parameters for a logical link are discussed in detail. A model has been developed to assess a set of logical links, representing WCS, with parameter up state function Ψ(t). Based on the objectives of a distributed IAS, dependability parameters can be weighted in order to adapt the DA on requirements of different links or systems. Exemplary measurements with a WCS are used to demonstrate the use of the up state function Ψ(t). Future investigations will focus on the development of a guideline for selecting weighting factors and action limit values according to application profiles [9]. The final target of this work is the development of a mechanism to prevent failures during operation or to accelerate self-recovery in case of failures. Thus, the resilience of future WA is addressed.

VIII. Acknowledgments

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