This document is a preprint of: A. Traßl, L. Scheuvens, T. Hößler, N. Franchi, and G. P. Fettweis, “On Dependability Metrics for Wireless Industrial Communications - Applied to IEEE 802.11ax,” *Proceedings of IEEE 5G World Forum*, 2019, accepted for publication. doi: 10.1109/5GWF.2019.8911652.

On Dependability Metrics for Wireless Industrial Communications – Applied to IEEE 802.11ax

Andreas Traßl[1,2], Lucas Scheuvens[2], Tom Hößler[2,3], Norman Franchi[2], and Gerhard P. Fettweis[1,2,3]
[1]Centre for Tactile Internet with Human-in-the-Loop (CeTI)
[2]Vodafone Chair Mobile Communications Systems, Technische Universität Dresden, Germany
[3]Barkhausen Institut, Dresden, Germany
Email: {andreas.trassl, lucas.scheuvens, tom.hoessler, norman.franchi, gerhard.fettweis}@tu-dresden.de

***Abstract*—Wireless communications solutions allow to exchange data in a flexible and cheap manner, especially in industrial use cases, which experience an increasing attraction in the context of 5G. However, high demands towards latency and dependability, especially for closed-loop control purposes, still prevent the wide deployment in these scenarios. Studies on specific opportunities and limitations of potential technologies are still lacking. In this paper we present a simulative dependability analysis of the upcoming WLAN standard IEEE 802.11ax for industrial use cases. Small-scale fading as well as system noise are considered as error sources. State-of-the-art is a dependability analysis by means of packet error ratios. However, such a ratio is not able to reflect application demands precisely. Thus, in this paper a dependability analysis is carried out based on the recently proposed metrics reliability and availability. For applications able to handle a certain number of consecutive packet errors, two new metrics are proposed, i.e., application reliability and application availability. It is shown that applications utilizing closed-loop control can achieve a vast dependability gain when tolerating packet errors. The gain is higher in cases when bursts of packet errors occur rarely. We conclude that IEEE 802.11ax has a promising dependability for different applications for middle to high SNRs.**

***Index Terms*—wireless industrial communications, industrial radio, closed-loop control, IEEE 802.11ax, availability, reliability**

I. INTRODUCTION

The factory of the future will excel through shorter product cycles as well as higher product individualization and overall flexibility. For this reason, production resources need to be reconfigured quickly in future, requiring a higher degree of mobility for each component. Wireless communications solutions are therefore highly welcome to extend established wired fieldbus systems. A wireless communications system is also advantageous with regards to moving machine parts, which nowadays use expensively installed and maintained wired connections. However, wireless solutions also have to meet the strict requirements towards transmission latency and dependability, especially for closed-loop control. In other words, such a communications system is expected to accomplish the vision of ultra reliable low latency communications (URLLC).

For the realization of such a system, different technologies are considered. Currently, the fifth generation (5G) of mobile communications systems is developed towards transmission latency and dependability and thus could be a promising candidate for closed-loop control purposes. Existing approaches are nowadays often customized mass market established communications solutions, e.g, the *iWLAN* system based on IEEE 802.11ac or *WirelessHART* based on IEEE 802.15.4. However, these approaches are not able to meet the strict requirements for advanced closed-loop control systems [1]. Currently, standardization for a new wireless local area network (WLAN) version IEEE 802.11ax is ongoing, which succeeds the widespread WLAN standards IEEE 802.11n and IEEE 802.11ac. IEEE 802.11ax implements changes which render the standard also more suitable to work along fieldbus systems.

Guaranteeing the dependability of a wireless communications system for control applications is a challenging task. Wireless communications systems have an unreliable nature due to interference, noise, and fading leading to possible packet errors. In a factory, packet errors can lead to production downtimes, production inaccuracies and even endanger humans. Hence, a dependability analysis from the development of a communications system to its deployment is of major importance . Traditionally, such analysis is carried out by means of packet error ratios (PERs), defined as the ratio between erroneous received packets and the total amount of packets. It is important to understand that the PER has little meaning to an application since it does not reflect the temporal domain, not allowing to evaluate, e.g., the consecutive downtime of a wireless link. At the same time, these consecutive downtimes are highly likely, since the channel only changes slowly. The dependability metrics reliability and availability are time dependent and thus preferable for an analysis. However, these metrics are only applicable to applications that depend on the reception of control signals in every controller sampling period. Advanced control applications may handle packet errors to a certain degree at cost of, e.g., application speed or control accuracy. Only by considering the imperfections of the wireless link, wireless industrial closed-loop control systems can be realized in future.

The contributions of this paper are as follows. We discuss the suitability of IEEE 802.11ax for industrial applications and point out possible limits. A special focus is laid on the dependability of the system. In a dependability analysis we apply the metrics availability and reliability, in contrast to the widely used PERs. Simultaneously, we propose the novel dependability metrics *application reliability* and *application availability*, which can be used to evaluate applications that

This document is a preprint of: A. Traßl, L. Scheuvens, T. Hößler, N. Franchi, and G. P. Fettweis, "On Dependability Metrics for Wireless Industrial Communications - Applied to IEEE 802.11ax," *Proceedings of IEEE 5G World Forum*, 2019, accepted for publication. doi: 10.1109/5GWF.2019.8911652.

are able to handle a certain number of packet errors. In this paper, applications designed to tolerate 3 or even 5 consecutive packet errors are considered. The presented analysis can be directly transferred to other communications systems like future 5G systems to advance the design and the deployment for industrial wireless closed-loop control.

II. Overview of the IEEE 802.11ax physical layer

The overall goal of the upcoming WLAN standard IEEE 802.11ax, also known as High-Efficiency WLAN, is to improve WLAN efficiency in high-density scenarios [2]. The main physical layer (PHY) enhancements compared to its direct predecessor IEEE 802.11ac are shortly introduced in the following.

OFDMA: IEEE 802.11ax will be the first ever WLAN standard employing orthogonal frequency division multiple access (OFDMA). The difference to orthogonal frequency division multiplexing (OFDM) is that blocks of subcarriers, so called resource units (RUs), can now be assigned to different users instead of assigning all available subcarriers to one user only. Hence, OFDMA allows more users to be served in parallel, while at the same time providing more finely granulated resources.

1024 QAM: New modulation and coding shemes (MCSs) are available in IEEE 802.11ax, establishing 1024 quadrature amplitude modulation (QAM) as the new maximum modulation. This option allows to further increase peak data rates under very good channel conditions.

Enhanced Dependability Options: Various new options to reduce the probability of packet errors are available in IEEE 802.11ax. Dual carrier modulation (DCM) is introduced as a frequency diversity option. The power of certain preamble fields can be boosted towards the remaining preamble fields and a signaling field is repeated if the newly introduced extended range option is used. Beamchange is a further option, which can be used to enhance the channel estimation accuracy. Moreover, midambles can now be utilized to update the channel estimation in fast varying channels.

Reduced Subcarrier Spacing: IEEE 802.11ax uses a four times smaller subcarrier spacing or rather a four times increased symbol duration compared to previous WLAN standards. Together with longer cyclic prefix (CP) durations, which are now available, this results in an enhanced robustness against multipath propagation or increased efficiency if the classical WLAN CP duration is used. However, the preamble overhead is increased due to the longer symbol duration. Therefore, two different modes, i.e., 1xHE-LTF and 2xHE-LTF, are introduced to shorten the channel estimation preamble field at the expense of estimation accuracy in comparison to the full-length mode 4xHE-LTF.

III. Costs, Latency, Interference

We start our discussion about the suitability of IEEE 802.11ax for industrial closed-loop control by analyzing possible problem-criteria, i.e., the cost of the system, as well as the latency and interference which can be expected when operating IEEE 802.11ax in the 5 GHz ISM band.

A. Cost

The communications system's cost is an important aspect for an industrial communications solution. A main argument for wireless solutions is that cables do not need to be installed and maintained costly [1], [3]. Moreover, when considering sensory monitoring applications, e.g., for predictive maintenance, the cost of the communications system has to relate to the manufactured component's cost that the communications solution is employed in.

In the past, WLAN systems had comparably cheap chips available due to the extreme number of manufactured units. It can be expected that IEEE 802.11ax as the successor of IEEE 802.11n and IEEE 802.11ac, which can be found in almost every consumer device, will also be widely used. Therefore, it is likely that IEEE 802.11ax will also stand out with cheap hardware prices. However, changes of manufacturers to adopt WLAN systems to industrial use cases can lead to tremendous price increases to compensate development efforts for comparatively low quantities.

B. Latency

IEEE 802.11ax cannot provide transmission latency guarantees. The practical end-to-end latency of IEEE 802.11ax systems depends on various factors. Propagation latency is induced by the distance-dependent propagation time of electromagnetic waves. For WLAN systems the propagation latency is negligible since transmitter and receiver are only a few meters apart. Access latency occurs when there is a transmission request, but the communications channel can only be accessed after a certain delay. WLAN systems operating in ISM bands use a carrier sense multiple access/collision avoidance (CSMA/CA) protocol on the media access control (MAC) layer for accessing the channel. The terminal has to wait a random time interval, the so called contention window, for channel access. The minimum contention window for the European 5 GHz ISM band is randomly chosen between 25 µs and 43 µs according to [4]. During waiting, every user has to observe the channel before accessing it as part of the clear channel assessment (CCA) method to check whether other users are already transmitting. If another transmission is in progress, a much higher access latency can be expected, which is problematic for WLAN-based control systems. In addition to access latencies, processing latencies occur in communications systems since some operations can only start if certain information or a certain number of bits are available. For example in WLAN systems, the preamble has to be awaited before processing of the data field can start. Furthermore every operation needs some time to generate output values from its input values. However, processing latencies are highly dependent on implementation and hardware.

C. Interference

Applications operating in ISM bands suffer from the possibility of interference due to other spectrum users, e.g., from private WLAN networks or from the weather radar. Interference lowers the availability of the communications system and

This document is a preprint of: A. Traßl, L. Scheuvens, T. Hößler, N. Franchi, and G. P. Fettweis, “On Dependability Metrics for Wireless Industrial Communications - Applied to IEEE 802.11ax,” *Proceedings of IEEE 5G World Forum*, 2019, accepted for publication. doi: 10.1109/5GWF.2019.8911652.

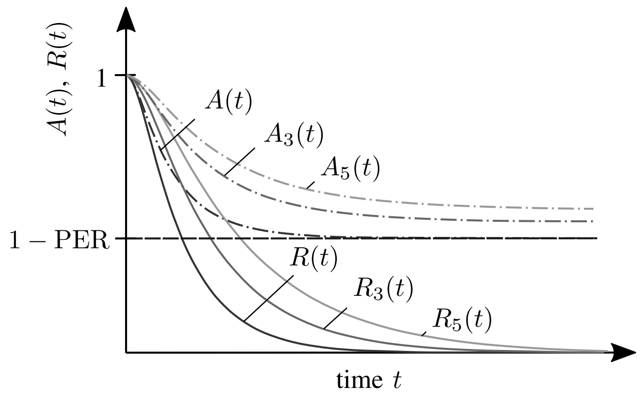

Fig. 1. Illustration of the dependability metrics PER, availability $A(t)$, reliability $R(t)$, application availability $A_p(t)$, and application reliability $R_p(t)$.

increases the channel access latency, as discussed previously. Hence, interference has to be considered when developing and deploying industrial communications solutions, e.g., by defining fail-safe modes. All in all, overly high interference can become problematic for industrial communications solutions operating in ISM bands. If steps to reduce the interference fail, other frequency bands have to be identified in which industrial communications solutions can be used.

IV. Dependability Metrics

To quantify the dependability of a communications system, various metrics may be used. State of the art is the analysis by means of PERs. Especially for control applications, the PER is not suitable in a dependability analysis. Further metrics for wireless communications systems originally used in reliability engineering were recently suggested [5], [6]. Our analysis is focused on the metrics availability and reliability since they have a temporal dependency contrary to PERs. A brief description of the used metrics is provided in the following. An overview of all utilized metrics is shown in Fig. 1.

A. Packet Error Ratio

The PER is defined as the ratio of the number of erroneous received packets N_{error} divided by the total packet number N_{total}. Thus, this metric is calculated by

$$\text{PER} = \frac{N_{\text{error}}}{N_{\text{total}}} \,. \tag{1}$$

The PER is a mean value and therefore is not capable to reflect information about up- or downtime durations. Since such up- or downtimes are of great importance for control applications, PERs are not suitable as a dependability metric for an application in most cases. However, PERs are well suited for feature comparisons, since in these cases it is of interest which option has a better performance on average.

B. Availability

Availability $A(t)$ in a wireless communications system is defined as the probability that the channel is in a state to successfully transmit data at a certain time t under the condition that the channel was operable at the begin of observation, $t = 0$. Since we consider slotted transmissions in this paper, we describe the respective time slot at integer multiples k of the sampling period T_{slot}. The slot $k = 0$ is the time slot starting at $t = 0$ containing a successful transmission by definition. Let X_k denote the event of successfully transmitting a packet in time slot k, then the communications availability is given by

$$A(t) = P(X_k|X_0) \,. \tag{2}$$

The limit of this metric as t approaches infinity equals $1 - \text{PER}$. Therefore, the availability of a communications system is always higher or equal to its PER. The lower the temporal correlation of the fading of successive packet transmissions becomes, the faster the availability will approach the PER. In scenarios, where the channel is slowly changing, it is highly likely that the channel is in an operable state after a first successful transmission.

C. Reliability

Reliability $R(t)$ in a wireless communications system describes the probability of exclusively successful packet transmissions during a time interval $[0, t]$, if the channel was operable at $t = 0$. Considering again slotted transmissions, reliability can be expressed as

$$R(t) = P(X_1 \cap X_2 \cap ... \cap X_{k-1} \cap X_k|X_0) \,. \tag{3}$$

As t approaches infinity, $R(t)$ will approach 0 as long as the systems availability $A(t) \neq 1$. This means that consecutive transmissions over a wireless channel will be guaranteed to fail at some time.

D. Application Availability and Application Reliability

Certain control applications may handle packet errors at the expense of, e.g., quality of control or application speed if only limited consecutive packet errors occur. In these cases the channel can be considered available in a more relaxed notion and can be used reliably for a longer time. Since the metrics reliability $R(t)$ and availability $A(t)$ do not account for such consecutive packet errors, we propose two new metrics to state dependability values for such applications: application availability $A_p(t)$ and application reliability $R_p(t)$. In this paper, p denotes the number of acceptable consecutive packet errors. The names of the proposed metrics refer to their ability to distinguish application-dependent quality of service. Let $X_{k,p}$ describe the event to successfully transmit data in time slot k or in any of the p time slots before, the metrics application availability $A_p(t)$ and application reliability $R_p(t)$ are given by

$$A_p(t) = P(X_{k,p}|X_0) \,, \tag{4}$$

$$R_p(t) = P(X_{1,p} \cap X_{2,p} \cap ... \cap X_{k-1,p} \cap X_{k,p}|X_0) \,. \tag{5}$$

This document is a preprint of: A. Traßl, L. Scheuvens, T. Hößler, N. Franchi, and G. P. Fettweis, "On Dependability Metrics for Wireless Industrial Communications - Applied to IEEE 802.11ax," *Proceedings of IEEE 5G World Forum*, 2019, accepted for publication. doi: 10.1109/5GWF.2019.8911652.

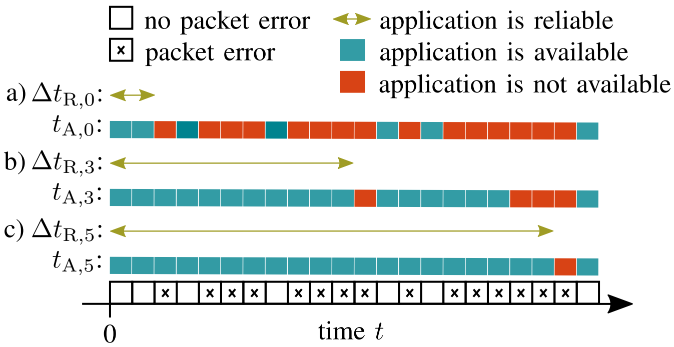

Fig. 2. Example of the time the application can be considered available $t_{A,p}$ and the interval the application works reliable $t_{R,p}$ for controllers able to handle a maximum of p consecutive packet errors.

Please note that as t approaches infinity, $A_p(t)$ will not approach $1 - \mathrm{PER}$ but rather a limit dependent on a ratio we term *application error ratio* (AER). Since we consider an application to fail only if more than p consecutive packet transmission failed, the limit $1-\mathrm{AER}_p$ for such an application is $1 - \mathrm{AER}_p = P(X_{k,p}) \geq 1 - \mathrm{PER}$.

Fig. 2 illustrates the concepts of application availability and application reliability for an exemplary sequence of failed and successfully transmitted packets: Depicted is the time an application can be considered available $t_{A,p}$ and the interval an application can be considered reliable $\Delta t_{R,p}$ for $p \in \{0, 3, 5\}$ acceptable packet errors. In the following analysis, we also focus on the investigation of $p \in \{0, 3, 5\}$ tolerable consecutive packet errors. The case $p = 0$, no packet errors can be tolerated, corresponds to the classical definition of availability and reliability.

TABLE I
CHOSEN SIMULATION PARAMETERS.

parameter	value
bandwidth	20 MHz
MCS	MCS0
RU size [subcarriers]	26 and 106
payload	30 byte
channel coding	convolutional code
channel estimation mode	2×HE-LTF
diversity options	STBC and RD
CP length	0.8 μs
transmit antennas	2
antenna spacing	0.5 wavelengths
channel model	[7]
K-factor	16.2 dB
movement speed [m/s]	1.1 and 4.4
angular spread	41°
receive antennas	2
time synchronization	realistic
frequency synchronization	realistic
channel estimation	LS
equalization	MMSE
pilot phase tracking	enabled
number of repetitions	up to 6×10^6

V. Dependability Analysis

To analyze the dependability of IEEE 802.11ax the previously discussed metrics are utilized. After we describe our evaluation procedure, the results are presented.

A. Simulation Model and Parameters

An IEEE 802.11ax link-level simulator from *Mathworks' WLAN system toolbox* of *MATLAB r2018b* is used. This link-level simulator is capable of creating and receiving IEEE 802.11ax PHY packets. The influence of the radio channel is simulated by means of a channel model, which simulates the 5 GHz ISM band in a small sized factory environment based on measurement data [7].

Multiple consecutive, equally sized downlink packets are simulated in a continuously changing channel. Packets are sent every millisecond with $T_{\mathrm{slot}} = 1\,\mathrm{ms}$, which corresponds to a sampling rate of $1\,\mathrm{kHz}$. This is a typical sampling rate for controllers operating in industrial closed-loop control systems, e.g., utilized by a state of the art robotic arm [8]. No retransmissions are utilized, since data gets outdated quickly in closed-loop control. At simulation start a radio channel realization is randomly chosen. The channel is then randomly varied for the duration of a packet and till the start of the next transmission slot. The state of the channel is then used at the start of the next packet. Consecutive packets are simulated for a duration of 30 ms. After this time the procedure is repeated according to the Monte Carlo method.

The simulation parameters are chosen according to Table I. These parameters were investigated to achieve a reliable PHY operation for the investigated channel model with a decently small packet duration and a sufficiently large number of operable users. Packets are simulated with the smallest available bandwidth of 20 MHz, which allows the greatest possible coexistence to other access points (APs). Only the lowest defined MCS, MCS0 (1/2 BPSK), is considered in order to achieve a reliable communications performance. The simulated PHY payload also including higher layer overhead for the investigated URLLC application is considered to be 30 bytes according to [9]. The available convolutional code is preferred over also available low density parity check (LDPC) codes, since they are superior for realizing low latency applications [10]. Since the investigated channel is only weak frequency-selective, the reduced channel estimation preamble mode 2xHE-LTF achieves the same performance as the full option 4xHE-LTF and is preferred since it results in shorter packet

This document is a preprint of: A. Traßl, L. Scheuvens, T. Hößler, N. Franchi, and G. P. Fettweis, "On Dependability Metrics for Wireless Industrial Communications - Applied to IEEE 802.11ax," *Proceedings of IEEE 5G World Forum*, 2019, accepted for publication. doi: 10.1109/5GWF.2019.8911652.

durations. However, the frequency diversity option DCM has a poor performance resulting from the weak frequency-selective property of the channel. Instead, the antenna diversity options space time block coding (STBC) in combination with two receive antennas used for receive diversity (RD) are simulated. This results in four diversity branches in total. The newly introduced options extended range and Beamchange are not utilized, since they are restricted to single user transmissions only. It is assumed that multi user transmissions are needed to connect all devices in industrial use cases. Since only a small sized factory with low path delays are investigated, the smallest available CP of $0.8\,\mu s$ was found to be sufficient. In this paper, investigations are carried out for channel model parameters which are preferable regarding the communications system performance, i.e., the highest suggested Rician K-Factor of $16.2\,\mathrm{dB}$ and the maximum angular spread of $41°$. However, to analyze the impact of the communications channel's change, different receiver speeds are investigated: $v = 4.4\,\mathrm{m/s}$, e.g., a receiver on the head of a robotic arm and $v = 1\,\mathrm{m/s}$, e.g., a receiver carried by an automated guided vehicle. Large-scale fading is not considered in these simulations. On the receiver side time synchronization and frequency synchronization are realistically carried out instead of assuming them to be ideal. No changes to the least squares (LS) channel estimation and minimum mean square error (MMSE) equalization algorithms from *MATLAB r2018b* were made. Pilot tones over the length of a WLAN packet are used to continuously update the frequency synchronization as intended by the pilot phase tracking method. Signaling preamble fields are assumed to be decoded correctly.

B. Simulation Results

The dependability metrics for the previously discussed simulation parameters are shown in Fig. 3 for different signal to noise ratios (SNRs). These SNRs were observed after the diversity combiner and are mean SNRs averaged over the small-scale fading. The metrics reliability $R(t)$ and application reliability $R_p(t)$ for fast receiver speeds ($v = 4.4\,\mathrm{m/s}$) and slow receiver speeds ($v = 1\,\mathrm{m/s}$) are shown in Fig. 3 a) and Fig. 3 c), respectively. Similarly, the metrics availability $A(t)$, application availability $A_p(t)$ and PER are plotted in Fig. 3 b) for fast receiver speeds and in Fig. 3 d) for slow receiver speeds.

When comparing the two investigated movement speeds, the decrease of reliability $R(t)$ and availability $A(t)$ is more rapid for high receiver speeds. This is the case, since at high movement speeds the channel is changing more rapidly from its guaranteed functioning state at $t = 0$. In Fig. 3 c) and Fig. 3 d) it is clearly visible that the availability curves tend $1 - \mathrm{PER}$ which is displayed as a dashed line. In addition, application availability $A_p(t)$ curves tend towards a different threshold $1 - \mathrm{AER}$. However, in Fig. 3 a) and Fig. 3 b) the limit of the metrics reliability $R(t)$ and application reliability $R_p(t)$ are not visible for all curves, since they reach zero level for a time $t \gg 30\,\mathrm{ms}$.

In all plots it can be observed that if consecutive packet errors can be tolerated, a higher dependability is achieved compared to the classical metrics availability $A(t)$ and reliability $R(t)$. The gain of tolerating consecutive packet errors is the higher the greater the mean SNR is. A reason is that bursts of packet errors are more likely for low SNRs. The reason for error bursts in this simulations are mainly fading dips, which lead to a received signal power being too small for successful decoding. If such an error state is reached it will be presumed for many transmission attempts, since the channel only changes slowly over several packets. The threshold of receive power which is needed at the receiver to successfully decode a packet is the higher the lower the mean SNR is. In other words, at low mean SNR values a big amount of noise is added to the signal which can only be compensated by high signal powers. However, it is more unlikely that a low receive power threshold is undershot compared to undershooting a higher threshold. Hence, as low thresholds for successfully decoding a packet occur at high mean SNRs, error bursts are more unlikely for these high mean SNRs.

For fast receiver speeds, which are plotted in Fig. 3 a) and Fig. 3 c), vast gains by tolerating packet errors can be observed. For example, if comparing the availability curves for a mean SNR of $10\,\mathrm{dB}$ with five tolerable packet errors and the curve for the same SNR without any tolerable packet errors in Fig. 3 c), a 100 times higher availability is achieved. This curve also overlays with the availability curve for a mean SNR of $15\,\mathrm{dB}$ when tolerating no packet errors. Similarly, the reliability curves in Fig. 3 a) for a mean SNR of $15\,\mathrm{dB}$ with three tolerable packet errors and for $20\,\mathrm{dB}$ SNR with no tolerable packet errors overlay. Hence, by designing the controller to be robust against 5 or 3 packet errors respectively, channels with a $5\,\mathrm{dB}$ worse SNR can achieve a similar performance in these cases. For higher SNR values even higher gains can be expected, since the impact of tolerating packet errors is higher when burst errors occur more rarely as explained before. However, for slow receiver speeds plotted in Fig. 3 b) and Fig. 3 d) the gain of tolerating packet errors is lower compared to the gain for high receiver speeds. The reason for this are again bursts of packet errors, which are more likely at low speeds. As the channel is varying more slowly a non-functioning state of the channel is presumed for a long time resulting in bursts of packet errors.

All in all, IEEE 802.11ax shows a promising dependability for advanced closed-loop control applications for middle to high mean SNRs. For a mean SNR of $20\,\mathrm{dB}$ a communications channel availability of roundly $1-10^{-6}$ can be expected for the simulated parameters. A controller which is sampled at $1\,\mathrm{kHz}$ controlling a robotic arm for $30\,\mathrm{ms}$ would have a success probability of $1 - 7 \times 10^{-4}$ at a mean SNR of $20\,\mathrm{dB}$.

VI. Conclusion

We conclude that the upcoming WLAN standard IEEE 802.11ax is a promising candidate for wireless industrial closed-loop control applications. Most importantly, IEEE

This document is a preprint of: A. Traßl, L. Scheuvens, T. Hößler, N. Franchi, and G. P. Fettweis, “On Dependability Metrics for Wireless Industrial Communications - Applied to IEEE 802.11ax,” *Proceedings of IEEE 5G World Forum*, 2019, accepted for publication. doi: 10.1109/5GWF.2019.8911652.

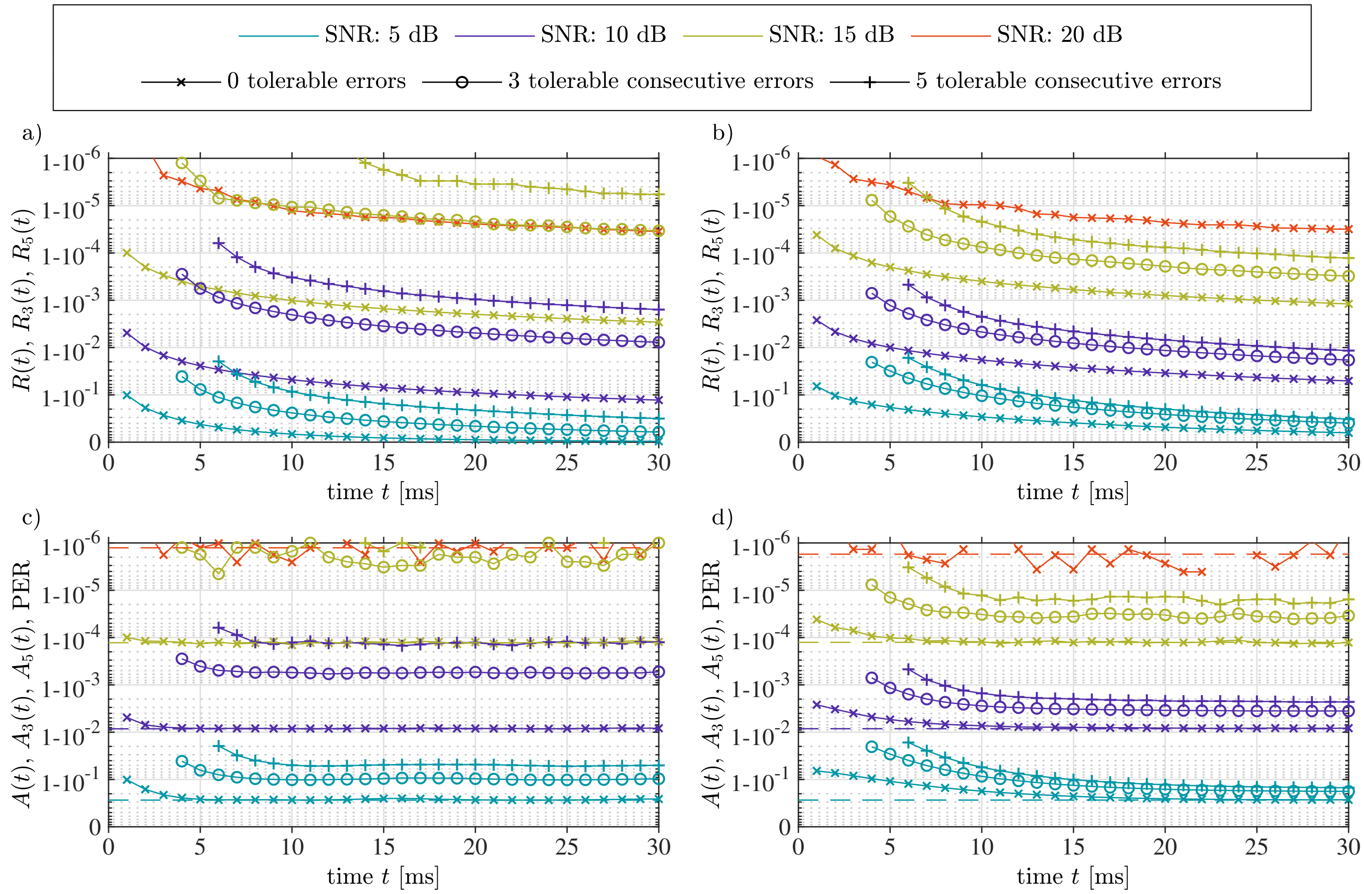

Fig. 3. IEEE 802.11ax dependability for the parameters from Table I: a) reliability and application reliability for $v = 4.4\,\mathrm{m/s}$ b) reliability and application reliability for $v = 1\,\mathrm{m/s}$ c) availability, application availability and PER for $v = 4.4\,\mathrm{m/s}$ and d) availability, application availability and PER for $v = 1\,\mathrm{m/s}$

802.11ax shows a good PHY dependability in industrial environments considering small-scale fading and noise. However, since it is usually operated in ISM bands, interference can degrade the dependability and lead to extensive channel access latencies. Our further conclusion is that by evaluating services in view of tolerable packet errors, vast dependability gains can be achieved. For analysis the newly introduced metrics application availability and application reliability can be used. The gain of tolerating packet errors is especially high when error bursts occur rarely, i.e., at high SNRs and fast changing communications channels.

Acknowledgments

This work was in part funded by the German Research Foundation (DFG, Deutsche Forschungsgemeinschaft) as part of Germany’s Excellence Strategy – EXC 2050/1 – Project ID 390696704 – Cluster of Excellence “Centre for Tactile Internet with Human-in-the-Loop” (CeTI) of Technische Universität Dresden. This work was also in part sponsored by the Federal Ministry of Education and Research within the program “Twenty20 – Partnership for Innovation” under contracts 03ZZ0528E – “fast robotics” – and 03ZZ0510F – “fast automation”, respectively. This research was co-financed by public funding of the state of Saxony/Germany. We thank the Center for Information Services and High Performance Computing (ZIH) at Technische Universität Dresden for generous allocations of computer time.

References

[1] A. Frotzscher, U. Wetzker, M. Bauer, M. Rentschler, M. Beyer, S. Elspass, and H. Klessig, “Requirements and current solutions of wireless communication in industrial automation,” in *2014 IEEE Int. Conf. on Commun. Workshops*, 2014.

[2] M. Afaqui, E. Garcia-Villegas, and E. Lopez-Aguilera, “IEEE 802.11ax: Challenges and requirements for future high efficiency WiFi,” *IEEE Wireless Commun.*, 2017.

[3] ETSI, “TR 102 889-2 V1.1.1; electromagnetic compatibility and radio spectrum matters (ERM); system reference document; short range devices (SRD); part 2: Technical characteristics for SRD equipment for wireless industrial applications using technologies different from ultra-wide band (UWB),” Tech. Rep., Aug. 2011.

[4] ——, “EN 301 893 V2.0.7; 5 GHz RLAN; harmonised standard covering the essential requirements of article 3.2 of directive 2014/53/EU,” Tech. Rep., Sept. 2016.

[5] T. Hößler, L. Scheuvens, N. Franchi, M. Simsek, and G. P. Fettweis, “Applying reliability theory for future wireless communication networks,” in *2017 IEEE 28th Ann. Int. Symp. on Pers., Indoor, and Mobile Radio Commun.*, 2017.

[6] T. Hößler, M. Simsek, and G. P. Fettweis, “Mission reliability for URLLC in wireless networks,” *IEEE Commun. Lett.*, 2018.

[7] A. Traßl, T. Hößler, L. Scheuvens, and G. Fettweis, “Deriving an empirical channel model for wireless industrial indoor communications,” in *2019 IEEE 30th Ann. Int. Symp. on Pers., Indoor, and Mobile Radio Commun.*, Sep. 2019.

[8] “Franka control interface overview,” https://frankaemika.github.io/docs/overview, accessed: 20-05-2019.

[9] ETSI, “TR 138 913 V14.2.0; 5G; study on scenarios and requirements for next generation access technologies,” Tech. Rep., May 2017.

[10] T. Hehn and J. Huber, “LDPC codes and convolutional codes with equal structural delay: a comparison,” *IEEE Trans. on Commun.*, 2009.