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Applying Reliability Theory for Future Wireless Communication Networks

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***Abstract*—Enhancing the connectivity reliability is one of the most challenging requirements for the design of future wireless communications systems. The scope of this paper is to leverage the existing tool set of reliability theory for enabling reliable communication in wireless systems. Definitions, concepts, and methods of reliability theory are applied and extended to wireless communications networks, which are modeled as a repairable system. The steady-state and transient system behaviour are considered. Two new key performance indicators (KPIs) for the reliability analysis of wireless communications systems are introduced, namely mean time to first failure (MTTFF) and interval reliability (IR), and a closed form expression is derived for the MTTFF. By evaluating an exemplary scenario, the trade-off between availability, reliability and throughput is discussed.**

***Index Terms*—5G, availability, interval reliability, mean time to first failure, reliability theory, URLLC.**

I. Introduction

One main objectives of the fifth generation (5G) of mobile communications systems is the support of diverse applications in a flexible and reliable way. The requirement dimensions comprise enhanced throughput, massive number of devices, and latency as well as connectivity reliability [1], [2]. Apart from enhanced Mobile Broadband (eMBB) and massive Machine Type Communications (mMTC), ultra-reliable low-latency communications (URLLC) is the third pillar of 5G networks. Possible use cases comprise, e.g., autonomous driving, industrial automation, robotics, health care, and mission-critical applications in IoT [3]. However, terms such as "availability" and "reliability", which are often used in the context of 5G research have not yet been unambiguously related to fundamental metrics of reliability theory and are used interchangeably. This can be noticed by comparing [1], [4], [5], [6].

Hence, this paper proposes to apply and adapt already existing definitions and concepts of reliability theory to wireless communications systems. We clearly identify and emphasize important differences and highlight potential causes of confusion.

Hereby, a wireless communications scenario for factory automation is considered, one of the URLLC use cases of 5G. Particularly, in this scenario high demands on availability and reliability of connectivity are to be met in order to control industrial automation applications in real time, requiring a maximum packet loss rate (PLR) of 10^{-9}, which can be interpreted as a downtime of $32\,\mu s$ over the course of one year.

One approach to satisfy the requirements of industrial automation with regard to cost-effectiveness and worldwide applicability is to develop wireless communications solutions, which can be operated in unlicensed frequency bands. The major challenge in this context, however, is the coexistence management of these unlicensed frequency bands. Thus, with respect to the strict reliability requirements, it is of special interest to determine the opportunities and the theoretical limits of this approach by means of reliability theory.

Reliability theory involves the development of mathematical methods in order to evaluate the reliability, maintainability, availability, and safety of technical components, equipment, and systems [7]. Basic fundamentals of reliability theory were introduced in the 1960s, e.g., in [8]. Reliability theory has developed well accepted definitions and concepts, which can also be applied to communications. Contributions include the assessment of reliability and performance of computer systems by means of probabilistic, discrete-state models [9], and examination of security aspects of communications systems from a reliability engineering perspective [10]. First approaches of adopting reliability theory concepts in order to enhance the reliability of cognitive radio networks are presented in [11]. However, metrics such as reliability, blocking probability, or mean time to first failure remain unmentioned. Instead, the authors only consider the steady-state probability of channel availability instead of investigating transition probabilities between operational and failed states.

The contributions of this paper are:

- Comparative summarization of fundamental reliability theory definitions, which are of special interest for research on URLLC in the context of 5G, and their adaptation to wireless systems.
- Proposal of the new key performance indicators (KPIs) *mean time to first failure* and *interval reliability* for the reliability analysis of wireless communications systems.
- Application of concepts of reliability theory to the system design of wireless communications sys-

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tems, i.e., how to

  - model a wireless communications system as a repairable system based on a continuous time Markov process with a finite discrete state space, and
  - introduce redundancy in order to improve availability and reliability.

- Evaluation of an exemplary scenario capturing the trade-off between availability, reliability and throughput. This significantly helps for the design of future wireless systems.

II. Notation

Throughout this paper the following notation is used. Bold Latin capital letters represent matrices and vectors. Unless otherwise specified, row vectors, denoted as $\boldsymbol{X} = [X_j]_{j=0}^{n}$, are used. The column vector of all ones is expressed by $\mathbf{1}$. The zero matrix of deducible size is denoted by $\mathbf{0}$. Subscripts indicate sub-matrices of the corresponding size. The matrix exponential of a square matrix $\boldsymbol{X}$ is defined as $\exp(\boldsymbol{X}) = \sum_{i=0}^{\infty} \frac{1}{i!}\boldsymbol{X}^i$, where $\boldsymbol{X}^0$ corresponds to the identity matrix $\boldsymbol{I}$. The Laplace transform of a function $F(t)$ is denoted as $F^*(s) = \mathcal{L}\{F(t)\}$. The derivative of a function $F(t)$ with respect to time t is represented by $\dot{F}(t)$. Variables based on acronyms are not printed in italics to avoid confusion with multiplication. The probability that an event E occurs is expressed by $\mathbb{P}\{E\}$.

III. Reliability Theory and Definitions of Parameters

Reliability theory has been introduced as a tool to analyze the life cycles and failures of technical systems. Important quantities used in reliability theory, e.g. availability, reliability, are expressed by probabilities and time durations. A common condition for all quantities is that the considered item is operational at time $t = 0$. The usual notion is that "up" is used for an operating state and "down" refers to a failed state, i.e., in repair if repairable. An item in wireless communications can be interpreted, e.g, as a component of a system, a system itself, a service or a wireless channel.

A. Availability

According to [12], an item is available, if it is in a state to perform a required function at a given instant of time or at any instant of time within a given time interval, assuming that the external resources, if required, are provided. On this basis the following availability quantities are derived in reliability theory.

The *instantaneous availability* $A(t)$, defined as [7]

$$A(t) = \mathbb{P}\{\text{"item is up at time } t\text{"}\} \ , \tag{1}$$

is the probability that the item is operating at a given instant of time t. Thus, it is also called *point availability*.

The *steady-state availability* A, defined as

$$A = \lim_{t\to\infty} A(t) \ , \tag{2}$$

enables to investigate the long-term probability that an item is available, which is one of the most important KPIs in reliability engineering. In literature, steady-state availability is often abbreviated with simply *availability* [7]. The steady-state availability can also be interpreted as the mean proportion of time the item is operational.

A quantity often used to specify reliability requirements in communications systems is PLR [5]. Strictly, the PLR characterizes the *steady-state unavailability*

$$\bar{A} = 1 - A \tag{3}$$

because it can be interpreted as the long-term probability the item is not operational.

B. Reliability

According to [12], reliability is defined as "the probability that an item can perform a required function under stated conditions for a given time interval." The *reliability*

$$R(t) = \mathbb{P}\{\text{"item is up throughout interval } [0,t]\text{"}\} \tag{4}$$

refers to failure-free operation of the item during an interval starting at time $t = 0$. It is also referred to as *survivor function* because it is the probability that the item survives the time interval $[0, t]$ and is still functioning at time t [13]. In the absence of repairs, adequate performance at time t implies adequate performance during $[0, t]$ [8]. Thus, the instantaneous availability $A(t)$ is equal to the reliability $R(t)$ of an item in the special case of no repairs. In general, the relation $A(t) \geq R(t)$ holds. In contrast to the concept of availability, the limiting value of $R(t)$ as t approaches infinity is given by $\lim_{t\to\infty} R(t) = 0$, whereas the steady-state availability (2) is nonzero except for the special case of no repairs [14]. Hence, referring to reliability without a time reference does not correspond to a valid statement. Moreover, in general, it is not possible to convert between reliability and steady-state availability because reliability changes over time whereas the steady-state availability is not time dependent. Therefore, adopting the definition of reliability to wireless communications systems is not obvious since reliability characterizes the probability that an item stays operational during the whole time interval starting with its instantiation and ending at a specified time t. In wireless systems, however, the reliability is defined as the amount (in %) 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 [6]. Referring to instantiation is plausible in the context of traditional reliability engineering evaluating the lifetime of actual items, such as

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electric devices or factory plants. However, this does not relate to any common KPI in wireless communications systems. Thus, the metric reliability is often mixed with availability. Please note, that, e.g., PLR relates to the concept of availability instead of reliability.

Closely related to reliability is the definition of *mean time to first failure* (MTTFF) because this parameter characterizes the average duration an item will operate before the first failure occurs [14]. The MTTFF can be determined by [13]

$$\mathrm{MTTFF} = \int_0^\infty R(t)\mathrm{d}t \ . \tag{5}$$

This metric is also often referred to as mean time to failure (MTTF) [14]. However, this may cause confusion to different quantities, such as mean up time or mean time between failures, especially if repairs are permitted [13].

We introduce the MTTFF as a new and promising KPI in the context of wireless communications systems, because this metric links reliability analysis with the time dimension, which is of particular importance to the 5G use case URLLC.

C. Interval Reliability

A quantity linking the concepts of reliability and availability is the *interval reliability*, because it is the probability that the considered item is operating at a specified time t and will continue to operate for an interval of duration Δt [8]:

$$\mathrm{IR}(t, \Delta t) = \mathbb{P}\left\{\text{"item is up throughout } [t, t+\Delta t]\text{"}\right\} . \tag{6}$$

Thus, the reliability $R(t)$ and the availability $A(t)$ functions are equal to the following special cases of interval reliability

$$A(t) = \mathrm{IR}(t, 0) \ , \tag{7}$$

$$R(t) = \mathrm{IR}(0, t) \ . \tag{8}$$

We propose to apply the KPI interval reliability to wireless communications systems, because it characterizes the probability that the system keeps operational during an arbitrary time interval. This is completely different from the reliability definition by 3GPP which can be interpreted as the mean proportion of time packets are successfully delivered [6].

D. Redundancy

In reliability theory, a system is often modelled to be composed of n components. One way to improve availability and reliability of a system is to introduce redundancy, i.e., employ one or more reserve components. A common assumption is the confinement to situations where it suffices to consider only a functioning state and a failed state for each component as well as the system [13]. A generic notation to express the concept of redundancy is the k-out-of-n ($k$oo$n$) structure. It characterizes a system which is functioning if and only if at least k of the n components are operational [15]. This can be illustrated by a reliability block diagram showing the logical connections of components necessary to fulfill the system function: A parallel structure corresponds to 1oo$n$ realizing full redundancy whereas $n$oo$n$ refers to a series structure without redundancy, which is visualized in Fig. 1. In wireless systems systems these components may reflect channels or links.

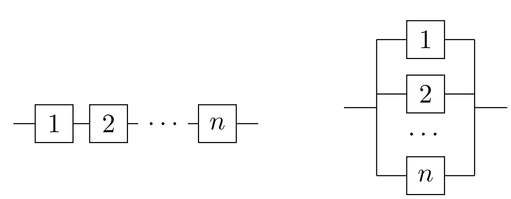
IV. System Model

A wireless communications system is considered comprising access points (APs), each communicating with a certain number of users. We assume a superordinate unit, the network manager (NM), connected to all APs in order to enable reliable wireless connectivity, e.g. by managing the coexistence of various unlicensed ISM frequency bands in a factory automation environment. The NM is considered to be equipped with mechanisms for dynamic selection of available frequency resources on the basis of spectrum sensing. The system is considered to operate in unlicensed frequency bands. Thus, co-channel interference is an important wireless access issue addressed by this paper. We assume, that an AP must leave a channel once an interferer begins to transmit over the same channel. Since the NM is able to prevent interference among the APs, this paper focuses on the special case of multiple interferers and one AP. Fading is neglected for simplicity.

From the AP's viewpoint, the considered system can be translated to terms of reliability theory. To do this, we identify channels with components according to the following:

$$\begin{aligned} \text{failed component} &\leftrightarrow \text{blocked channel by interferer} \\ \text{repaired component} &\leftrightarrow \text{released channel by interferer} \end{aligned}$$

The AP has the capability to sense all n channels and transmit over an arbitrary number of channels $k = 1, 2, \ldots, n$ channels simultaneously. This meets the general $k$oo$n$ redundancy concept in reliability theory. Single connectivity relates to $k = 1$, whereas $k > 1$ implies multi-connectivity.



(a) Series structure, $n$oo$n$ (b) Parallel structure, 1oo$n$

Fig. 1. Reliability block diagram for series and parallel structure

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Continuous time Markov models with a finite discrete state space are a standard tool used to describe a system's temporal behaviour in many fields of reliability engineering [16]. Thus, the considered wireless communications system is modelled from the AP's viewpoint as an irreducible, homogeneous Markov process. Let the finite system state j reflect the number of channels blocked by interferers. Hence, a system with n channels has $n+1$ states. System state j is increased by one whenever a free channel becomes blocked by a interferer and decreased by one when a blocked channel is released. The state space is partitioned into the set of "up" states $\mathcal{U}$ and the set of "down" states $\mathcal{D}$ according to

$$\mathcal{U} = \{0, 1, \ldots, n-k\} \ , \tag{9}$$

$$\mathcal{D} = \{n-k+1, n-k+2, \ldots, n\} \tag{10}$$

with the cardinalities

$$U = |\mathcal{U}| = n - k + 1 \ , \tag{11}$$

$$D = |\mathcal{D}| = k \ . \tag{12}$$

Furthermore, the system investigated in this paper is based on the following assumptions:

- The interferer's arrival rate λ is the AP's channel failure rate.
- The interferer's service rate μ is the AP's channel repair rate.
- The rates λ and μ are constant and independent, where λ and μ being constant correspond to an equal probability at all times for an interferer to appear or leave, respectively.
- Every interferer's arrival and leaving is self-revealing. This means that the NM will sense the experienced interference at at all times and immediately recognizes a state-change.
- A released channel is "as good as new". Switching is perfect and immediate, i.e., if a channel used by a AP becomes blocked, the AP's complete traffic will be transmitted over an alternative free channel without delay or loss of information.
- No bursts are considered, i.e., the probability that more than one channel is blocked or released at the same time is negligible and no state can be skipped.

The resulting birth-death Markov process is visualized in Fig. 2. The state equations are expressed by

$$\dot{P}_j(t) = \lambda_{j-1} P_{j-1}(t) - (\lambda_j + \mu_j) P_j(t) + \mu_{j+1} P_{j+1}(t) \quad \text{for } j = 0, 1, \ldots, n \ , \tag{13}$$

where $P_j(t)$ is the state probability that j channels in the system are blocked at time t, the first derivative of $P_j(t)$ with respect to time is denoted by $\dot{P}_j(t)$ and $P_j(t) \equiv 0$ for $j < 0$ or $j > n$ [15]. The differential equations (13) may be written in matrix terms as

$$\dot{\boldsymbol{P}}(t) = \boldsymbol{P}(t) \cdot \boldsymbol{M} \ , \tag{14}$$

with the tridiagonal transition matrix $\boldsymbol{M}$, the state probability vector $\boldsymbol{P}(t)$, and the state probability derivative vector $\dot{\boldsymbol{P}}(t)$.

Considering the introduced assumptions, the system transition parameters of the target wireless communications scenario are summarized as:

$$\lambda_j = \lambda \quad \text{for} \ \ 0 \leq j < n \ , \tag{15a}$$

$$\mu_j = j\mu \quad \text{for} \ \ 0 < j \leq n \ , \tag{15b}$$

assuming $\lambda, \mu \in \mathbb{R}^+$.

V. Determination of Reliability Quantities

In this section, we apply the initially stated definitions of fundamental reliability quantities to the introduced wireless communications scenario from the AP's viewpoint. A wireless communications system is hereby modeled as a repairable system. The general concept of $k$oo$n$ redundancy is taken into account as well because all determined metrics depend on k, the number of channels a AP requests simultaneously. The case of single connectivity, equivalent to $k = 1$, simplifies the following metrics. The steady-state is considered as well as the transient system behaviour.

A. Steady-State Availability

The wireless communications system is instantaneously available if it is in one of the system up states aggregated in $\mathcal{U}$. Thus, the instantaneous availability of the considered Markov process is defined as

$$A_k(t) = \sum_{j \in \mathcal{U}} P_j(t) = \sum_{j=0}^{n-k} P_j(t) \ . \tag{16}$$

The state probabilities $P_j(t)$ is obtained by solving the differential equations (14). In many applications only the steady-state situation is of interest. The steady-state availability of the system results as:

$$A_k = \sum_{j \in \mathcal{U}} P_j = \sum_{j=0}^{n-k} P_j \ , \tag{17}$$

with the steady-state probabilities $P_j = \lim_{t\to\infty} P_j(t)$.

We apply transition rates (15) for the introduced scenario to the steady-state probabilities for birth-death Markov processes [17], obtaining

$$P_j = \frac{\rho^j}{j!} \cdot \left[1 + \sum_{\ell=1}^{n} \frac{\rho^\ell}{\ell!}\right]^{-1} \tag{18}$$

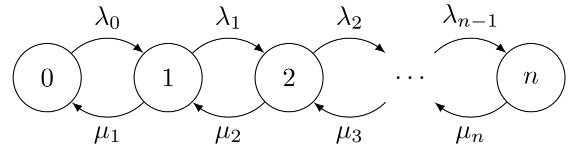

Fig. 2. Birth-Death Markov Process based on [14]

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with the ratio $\rho = \lambda/\mu$. Thus, as a contribution of this paper, it is determined that for the considered wireless communications scenario the steady-state probabilities and consequently the AP's steady-state availability purely depend on the ratio ρ instead of the actual rates λ and μ under the specified conditions:

$$P_j = f(\rho) \Rightarrow A_k = g(\rho) \ . \tag{19}$$

The complement of the system availability A_k is the system unavailability given by

$$\bar{A}_k = 1 - A_k = \sum_{j \in \mathcal{D}} P_j = \sum_{j=n-k+1}^{n} P_j \ . \tag{20}$$

It may be interpreted as an important KPI in the context of wireless communications, e.g., channel blocking probability or PLR caused by interference.

B. Reliability

To determine the reliability function of the considered system model, all failed states are assumed to be *absorbing* because the concept of reliability characterizes the probability that a system does not leave the set $\mathcal{U}$ of up states during the time interval $[0,t]$ [15]. By setting the transition rates from the failed states equal to zero, we derive the modified Markov process with the transition rates showed in Fig. 3. Similarly to eq. (14), the state equations can be summarized as

$$\dot{\hat{\boldsymbol{P}}}(t) = \hat{\boldsymbol{P}}(t) \cdot \hat{\boldsymbol{M}} \ . \tag{21}$$

Solving these differential equations leads to the state probabilities $\hat{P}_j(t)$ of the modified Markov model. On this basis, the reliability function is obtained as

$$R_k(t) = \sum_{j \in \mathcal{U}} \hat{P}_j(t) = \sum_{j=0}^{n-k} \hat{P}_j(t) \ . \tag{22}$$

The AP's reliability $R_k(t)$ is a time dependent function converging to zero. Thus, referring to a reliability value without specifying parameter t is not a valid statement.

C. Mean Time to First Failure

Since the MTTFF is defined as the improper integral (5) it can be determined using Laplace transformation of the reliability function and subsequently setting the Laplace parameter to zero [13].

$$R_k^*(s) = \mathcal{L}\left\{R_k(t)\right\} = \int_0^\infty R_k(t) \exp(-st)\, \mathrm{d}t \ . \tag{23}$$

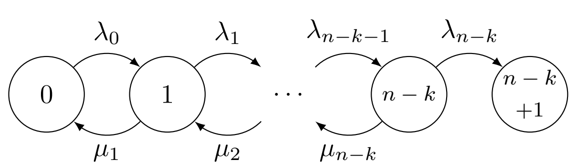

Fig. 3. Modified Birth-Death Markov Process

$$\rightarrow \mathrm{MTTFF}_k = R_k^*(0) = \int_0^\infty R_k(t)\, \mathrm{d}t \ . \tag{24}$$

This paper presents the following closed form expression of the MTTFF for the considered $k\mathrm{oo}n$ structure:

$$\mathrm{MTTFF}_k = \frac{1}{\lambda} \sum_{j=0}^{n-k} \rho^{j-n} \sum_{\ell=k}^{n-j} \rho^{\ell} \prod_{i=\ell}^{n-j-1} (n-i) \, , \tag{25}$$

assuming that all n channels are available at $t=0$.

This can be proven by inserting the summands of statement (25), denoted by

$$S_j = \frac{1}{\lambda \rho^{n-j}} \sum_{\ell=k}^{n-j} \rho^{\ell} \prod_{i=\ell}^{n-j-1} (n-i) \, , \tag{26}$$

for each component $\hat{P}_j^*(0)$ of $\hat{\boldsymbol{P}}^*(0)$ in the equations

$$-\boldsymbol{P}(0) = \hat{\boldsymbol{P}}^*(0) \cdot \hat{\boldsymbol{M}} \ , \tag{27}$$

which correspond to the Laplace transforms of equations (21) with $s=0$, resulting from eq. (22) with (24) .

As a further contribution of this paper, we emphasize that, in contrast to the steady-state availability A_k, the AP's MTTFF_k depends on ρ and λ:

$$\mathrm{MTTFF}_k = h(\rho, \lambda) \ . \tag{28}$$

We propose to introduce the KPI MTTFF_k to the research on wireless communications because this metric enables to evaluate the reliability of the wireless communications system from the AP's viewpoint taking into account the actual rates λ and μ. In contrast to the AP's reliability function (22), specifying an instant of time is not necessary.

D. Interval Reliability

A closed form expression of the interval reliability for Markov models is given by [16]

$$\mathrm{IR}(t, \Delta t) = \boldsymbol{P}(0) \exp(t\boldsymbol{M}) \begin{pmatrix} \boldsymbol{I}_{UU} \\ \boldsymbol{0}_{DU} \end{pmatrix} \exp(\Delta t \boldsymbol{M}_{UU}) \boldsymbol{1}_U \ . \tag{29}$$

The considered Markov process starts at time $t=0$ according to the initial probability vector $\boldsymbol{P}(0)$.

We believe that the interval reliability in many cases mixed with the reliability metric, whereas it describes the likelihood not to experience a failure during a freely chosen time period $[t, t+\Delta t]$, which strongly relates to the reliability definitions in wireless systems in various standardization bodies. Interval reliability can be applied *before* a transmission is initiated and it can be evaluated *recurrently* for every individual transmission, to give the sender (or sending application) an indication about the success rate of that undertaking. The application can then decide for itself if the success probability is high enough or not, e.g., by comparing it to an application specific threshold value. This way, resource wasting (transmission attempts due to an unknown network status with high risk of failure) can be avoided.

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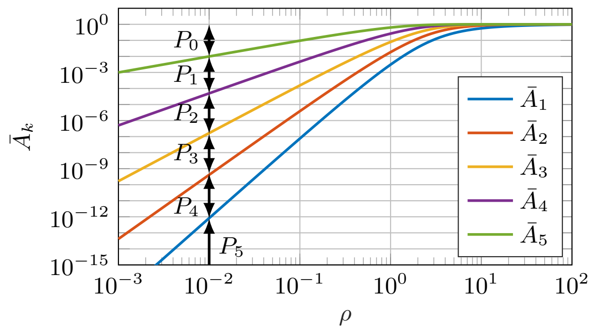

Fig. 4. Steady-state probabilities, steady-state unavailability, $n = 5$

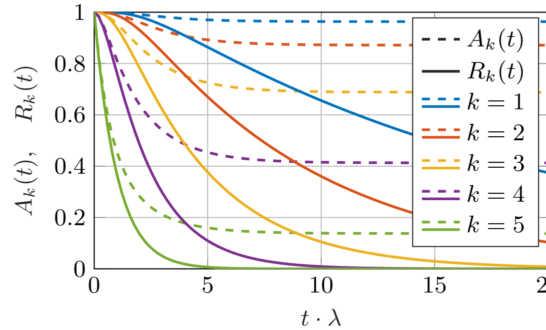

Fig. 5. Instantaneous availability and reliability, $n = 5$, $\rho = 2$

We propose to apply the KPI "interval reliability" to wireless communications, because it generalizes the concept of reliability from considering intervals starting at $t = 0$ to arbitrary intervals, which correspond to a more realistic evaluation intent in the context of wireless communications systems.

VI. Evaluation Scenario and Results

In this section, the introduced reliability quantities are evaluated for an exemplary scenario. These include

- steady state availability,
- transient behaviour of availability, reliability, and interval reliability.

We assume $n = 5$ independent wireless channels as an example. An AP is able to sense all of them and transmit over an arbitrary combination, i.e., $k = 1, 2, \ldots, n$. The considered wireless access issue is co-channel interference between interferers and the AP using the same transmission frequency.

The results regarding the steady state with respect to ρ are shown in Fig. 4. The lines represent the steady-state unavailabilities $\bar{A}_k$ and the differences between the lines correspond to the steady-state probabilities P_j (as shown exemplary for $\rho = 10^{-2}$). Higher degrees of redundancy, which are equivalent to smaller values of k, reduce the steady-state unavailability. The figure shows that introducing redundancy improves availability especially for small values of ρ.

Interpreting the steady-state unavailability as PLR, as assumed in this paper, enables system design recommendations with respect to the expected ratio ρ of a considered environment. These results facilitate the numerical trade-off analysis between throughput and availability (with throughput being modeled as a linear function of channels used for transmission). For the exemplary value of $\rho = 10^{-2}$ using $k = 2$ channels simultaneously instead of $k = 1$ means doubled throughput but availability decreases by a factor > 100.

The instantaneous availability and reliability are plotted in Fig. 5 over time normalized to λ for the exemplary value of $\rho = 2$ (chosen for good readability) . At $t = 0$ all values are equal to one because it is assumed that all channels are free at system start. As expected, the instantaneous availability as well as the reliability are higher for smaller values of k because of redundancy. It is shown that $A_k(t) \geq R_k(t)$ and the fact that the instantaneous availabilities $A_k(t)$ converge to the steady-state availability $A_k = \lim_{t\to\infty} A_k(t)$ while the reliabilities $R_k(t)$ converges to zero for $t \to \infty$. Here, the absolute values of λ and μ (as opposed to only their ratio ρ) influence how fast these limits are approached.

Consequently, the MTTFF also depends on the actual values of λ and μ as Table I demonstrates for a 4oo5 system. Hence, a system is conceivable with a fixed steady-state availability A_k but the MTTFF_k may vary by several orders of magnitude. The obtained constant steady-state unavailability $\bar{A}_4$ is low but the MTTFF_4, derived by the reliability function according to eq. (25), varies between 1 s and more than 11 days.

The MTTFF_k, normalized to λ, is shown in Fig. 6 for $k = 1, 2, \ldots, n$. Similar to the steady-state availability, the MTTFF_k is higher for larger degrees of redundancy, i.e., for smaller values of k. For smaller values of ρ the differences increase and the impact of redundancy is higher. In the special case of no redundancy for $k = n$ (the AP needs all resources), the MTTFF_k reduces to $\mathrm{MTTFF}_n = 1/\lambda$. It is independent of μ because the first channel blockage causes a failure for the AP.

Interval reliability represents a reliability metric for arbitrary interval start times and durations. This is exemplary visualized for $k = 2$ and $\rho = 2$. It is illustrated that the interval reliability links the concepts of availability and reliability because the special cases of interval reliability setting $\Delta t = 0$ or $t = 0$ are

TABLE I
Comparison of Steady-State Unavailability and MTTFF

$\lambda \cdot$ s	$\mu \cdot$ s	ρ	$\bar{A}_4$	MTTFF_4
10^{-3}	1	10^{-3}	$5 \cdot 10^{-7}$	11.5 days
10^{-1}	10^2	10^{-3}	$5 \cdot 10^{-7}$	2.8 hours
10^1	10^4	10^{-3}	$5 \cdot 10^{-7}$	100 s
10^3	10^6	10^{-3}	$5 \cdot 10^{-7}$	1 s

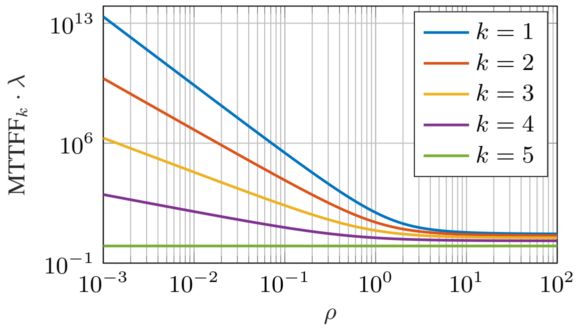

Fig. 6. Mean time to first failure, $n = 5$

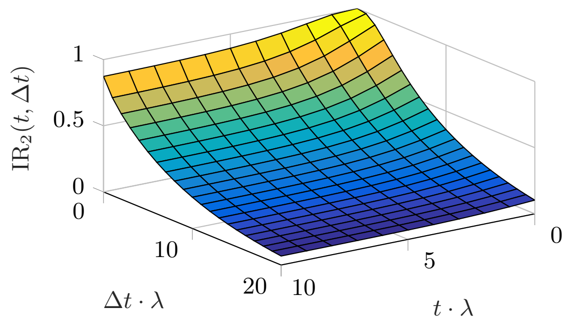

Fig. 7. Interval reliability, $k = 2$, $n = 5$, $\rho = 2$

equal to the instantaneous availability and reliability over time, respectively. Since the availability converges to the steady-state availability, the interval duration Δt has the major impact on interval reliability. As long as a transmission has not been initiated, the interval reliability function can be evaluated in the dimension of time t. Once a transmission is started, the interval reliability function develops in the dimension of the interval duration Δt.

VII. Conclusion

Reliability theory provides a set of mathematical tools, which are applied to evaluate and improve the life cycle performance of products. In this paper, we demonstrate that it is possible and beneficial to leverage this tool set and transfer it to a wireless communications scenario.

Especially in the context of 5G, the usage of appropriate definitions and a proper distinction between different metrics, such as "availability" and "reliability", is essential. We have shown that "availability" is an outgrown quantity for wireless communications. Instead, we introduced the term "interval reliability" for wireless systems and presented a closed form expression for MTTFF of a $k$oo$n$ scenario. Using these more distinguished KPIs when referring to URLLC may sharpen discussions about the topic. For a factory automation scenario, we determined that steady-state availabilities only depend on ρ, reflecting the ratio of the AP's channel failure rate λ and its channel repair rate μ. In contrast, MTTFF is influenced by their absolute values. Accordingly, our results demonstrate that multiple system designs with the same steady-state availability can exhibit significantly varying MTTFF. Moreover, we present the benefit of introducing redundancy capturing a numerical trade-off analysis between throughput and availability.

It is of interest to extend this work by considering mobility aspects, a variant number of users as well as fluctuating characteristics of the wireless channel, e.g., path loss, shadowing, and multipath fading. These investigations are important steps to enable key challenges of future networks and especially URLLC, one of the expected main use cases of 5G.

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