This document is a preprint of: T. Hossler, M. Simsek and G. Fettweis, “Joint Analysis of Channel Availability and Time-Based Reliability Metrics for Wireless URLLC,” in Proceedings of IEEE Global Communications Conference (GLOBECOM 2018), Abu Dhabi, UAE, Dec 2018. DOI:10.1109/GLOCOM.2018.8647801

Joint Analysis of Channel Availability and Time-Based Reliability Metrics for Wireless URLLC

Tom Hößler*, Meryem Simsek†, and Gerhard P. Fettweis*
*Vodafone Chair Mobile Communications Systems, Technische Universität Dresden, Germany
Email: {tom.hoessler, meryem.simsek, gerhard.fettweis}@tu-dresden.de
†International Computer Science Institute, Berkeley, USA
Email: simsek@icsi.berkeley.edu

***Abstract*—The fifth-generation (5G) of mobile networks are supposed to address radically new types of applications that have not been possible with previous generations of wireless technologies. Ultra-Reliable Low-Latency Communication (URLLC) is one 5G use case category imposing strict requirements on the availability, reliability, and latency together with zero mobility interruption. Aiming for a common understanding, we put forward a comprehensive description of performance metrics based on reliability theory focusing on availability and reliability metrics as a function of time. We establish a link to wireless communications by studying Rayleigh fading channels in a multi-connectivity system. The reliability metric definitions and analytic models presented in this paper contribute to enable a systematic and accurate performance analysis for URLLC. Numerical evaluations demonstrate the importance of considering not only availability alone but combinations of availability and time-based reliability statistics jointly.**

***Index Terms*—5G, availability, reliability theory, URLLC, wireless networks**

I. Introduction

A main objective 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 throughput, capacity, number of devices and costs, but also availability, reliability and latency are important [1]. Apart from enhanced Mobile Broadband (eMBB) and massive Machine Type Communications (mMTC), ultra-reliable low-latency communications (URLLC) is the third pillar of 5G. Thus, 5G is expected to underpin the emergence of the Tactile Internet, in which ultra-reliable and ultra-responsive network connectivity will enable to deliver real-time control and physical tactile experiences remotely [2].

Within the context of 5G, key performance indicators (KPIs) such as "availability" and "reliability" are often used interchangeably and considered as the percentage of successful transmissions, e.g., the required reliability of $1 - 10^{-9}$ for wireless factory automation [3], [4]. Especially in the area of URLLC, reliability is connected to time-based requirements by latency deadlines, often in the (sub-)millisecond range, e.g., $250\,\mu\mathrm{s}$ for factory automation, $3\,\mathrm{ms}$ in smart grids, and $10\,\mathrm{ms}$ for intelligent transport systems (ITS) [4]. Besides, the targeted zero mobility interruption, which is obviously the optimal value, is the only explicit time attribute in the current discussion on reliability of 5G [5]. However, time-based reliability metrics, such as mean up time, mean down time, or mean time to failure, which are fundamental and well accepted tools in reliability theory, remain almost unmentioned in wireless communications [6]. Only a few research activities have been performed aiming to leverage methods of reliability theory to wireless channels with respect to time aspects: In [7], concepts of reliability theory are applied and extended to wireless communications networks, which are modeled as repairable systems. Channel available and unavailable time intervals are modeled based on the channel occupancy status in [8]. However, the availability and reliability analysis is restricted to cognitive radio networks. Further research activities linking wireless communications and reliability theory focusing on time aspects is necessary to refine the discussion on URLLC, which aims for reliably linking systems from different domains, such as wireless communications, factory automation, etc.

In this work, we utilize fundamental reliability theory to foster the understanding of the relevant terms for wireless communications and demonstrate that a joint consideration of time-based reliability metrics and channel availability is of great importance for designing future wireless communications systems. The main contributions of this paper are as follow.

- Comprehensive summary of fundamental reliability theory definitions that are of special interest for URLLC research.
- Derivation of the KPIs *mean up time*, *mean down time*, and *mean time between failures* for the reliability analysis of wireless communications systems, obtaining closed form expressions for the special case of Selection Combining of multiple Rayleigh fading links.
- Application of concepts of reliability theory to the system design of wireless communications systems, i.e., how to
  - model a wireless communications system with Rayleigh fading links as a repairable system based on continuous-time Markov chains (CTMC), and

  - introduce redundancy by means of frequency diversity to improve availability and reliability.
- Evaluation of an exemplary scenario, corresponding to Selection Combining, capturing the trade-off between the number of links used for multi-connectivity, fading margin, velocity, and carrier frequency regarding channel availability, and time-based reliability metrics.

II. System Model

The operations within a wireless network can be interrupted by various causes of failures, e.g., insufficient signal power, bad signal quality due to fading or interference, handover failures, or even software and hardware bugs. In this paper, we concentrate on multi-path propagation as a cause of failure for the wireless communications system and consider a single user connected to n wireless links simultaneously. Assuming that each link consists of many individual paths without a dominant component, Rayleigh-fading channels are considered. We focus on links which are separated in frequency at least by the coherence bandwidth leading to independent fading. Compensation of path loss and shadowing by transmit power or automatic gain control is assumed. However, the proposed model can also be extended to wireless systems including path loss and shadowing, as well as other channel models.

A. Single Rayleigh-Fading Link

The system can be described by existing terms from reliability theory identifying channels as repairable components. If and only if messages can be successfully transmitted and received via a channel, the latter is assumed to be operational. The usual notion is that "up" is used for an operational state whereas "down" refers to a failed state, i.e., in repair if repairable. A Rayleigh-faded signal can be successfully received if the instantaneous power $p(t)$ is above a certain threshold $p_{\min}$, which may be determined by the receiver's hardware sensitivity. Thus, we distinguish between two states by introducing the random variable channel state

$$Y(t) = \begin{cases} 0, & \text{if } p(t) < p_{\min}, \text{"down", "failed"} \\ 1, & \text{if } p(t) \geq p_{\min}, \text{"up", "operational"} \end{cases} . \tag{1}$$

The considered wireless channel can be interpreted as a repairable item based on the Gilbert-Elliot model, which was created to characterize independent impulsive noise and has been successfully used to analyze error patterns of wireless transmission channels [9], [10]. The average (non-)fade duration of a Rayleigh-faded signal can be determined by level crossing analysis. Their reciprocals characterize the transition rates between the two channel states, which we denote as failure rate λ and repair rate μ according to [11]

$$\lambda = \sqrt{\frac{2\pi}{F}} f_{\mathrm{D}} \ , \tag{2a}$$

$$\mu = \frac{\sqrt{\frac{2\pi}{F}} f_{\mathrm{D}}}{\exp \frac{1}{F} - 1} \ , \tag{2b}$$

where $F = p_{\mathrm{avg}}/p_{\min}$ represents the fading margin with the average receive power p_{avg}. The maximum Doppler frequency is characterized by $f_{\mathrm{D}} = vf/c$, where f is the carrier frequency of the signal and c is the speed of light. The relative velocity between transmitter, receiver, and scatterers is denoted as v. The rates λ and μ are assumed to be constant implying that the random fading process does not change its statistical properties with time. Every fading is self-revealing. This means that every state change is recognized immediately. The probability that more than one channel enters or leaves the failed state at the same time is negligible.

B. Multiple Rayleigh-Fading Links

In reliability theory, a system is often modelled to be composed of n components. One way to improve the availability and reliability of a system is to introduce redundancy, i.e., employ one or more reserve components. A generic notation to express the concept of redundancy is the k-out-of-n ($k$oo$n$) structure. It characterizes a system that is functioning if and only if at least k of the n components are operational [12]. The general $k$oo$n$ redundancy concept can be adopted to wireless communications by assuming that the user's communication is successful if at least $k \in \{1, 2, \ldots, n\}$ out of n wireless links are operational. It might not be always required that all k links have to be operational. Hence, we focus on a special case which is known as selection combining in wireless communications. The special case of data sent redundantly over each link and the user performing Selection Combining corresponds to $k = 1$, because the best (1oo$n$) link is selected. Thus, it is sufficient if at least one link is operational.

We model the considered wireless communications system as an irreducible, homogeneous CTMC. Let the finite system state j be defined as the number of channels in an operational state. Hence, a system with n channels has $n+1$ states, including the cases that none of the n channels are operational. The system state j is decreased by one whenever an operational channel enters a failure and increased by one when a failed channel is operational again, which can be interpreted as a channel repair. The state space is partitioned into the set of "up" states $\mathcal{U}$ and the set of "down" states $\mathcal{D}$ according to

$$\mathcal{U} = \{k, k+1, \ldots, n\} \ , \tag{3a}$$

$$\mathcal{D} = \{0, 1, \ldots, k-1\} \ . \tag{3b}$$

The resulting birth-death CTMC is visualized in Fig. 1. The state equations are expressed by

$$\dot{P}_j(t) = \mu_{j-1} P_{j-1}(t) - (\mu_j + \lambda_j) P_j(t) + \lambda_{j+1} P_{j+1}(t) \quad \text{for } j = 0, 1, \ldots, n \ , \tag{4}$$

where $P_j(t)$ is the state probability that there are j failed channels in the system 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 $j > n$ [12]. The differential equations (4) of this CTMC may be written in matrix terms as

$$\dot{\boldsymbol{P}}(t) = \boldsymbol{P}(t) \cdot \boldsymbol{M} \ , \tag{5}$$

This document is a preprint of: T. Hossler, M. Simsek and G. Fettweis, "Joint Analysis of Channel Availability and Time-Based Reliability Metrics for Wireless URLLC," in Proceedings of IEEE Global Communications Conference (GLOBECOM 2018), Abu Dhabi, UAE, Dec 2018. DOI:10.1109/GLOCOM.2018.8647801

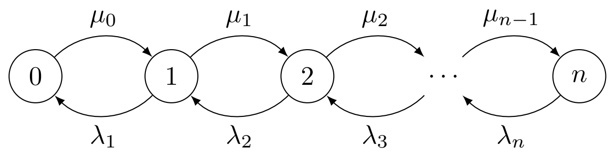


Fig. 1. Birth-Death CTMC

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

Based on the assumptions of independent links with equal fading margin F and maximum Doppler shift f_{D}, we derive the system transition parameters of the considered wireless communications scenario as

$$\lambda_j = j\lambda \qquad \text{for} \quad 0 < j \leq n \ , \tag{6a}$$
$$\mu_j = (n-j)\mu \quad \text{for} \quad 0 \leq j < n \ . \tag{6b}$$

III. Reliability Quantities

Important quantities used in reliability theory express probabilities and time duration. In this section, we summarize definitions of fundamental reliability quantities and apply them to the considered wireless communications scenario from the user's viewpoint. A wireless communications system is hereby modeled as a repairable system. An item in wireless communications can be interpreted, e.g, as a component of a system, a system itself, a service or a channel. According to the introduced system model, we identify the components of a system with wireless channels and apply the concept of $k\text{oo}n$ redundancy. Consequently, the indices k, n emphasize that a quantity depends on the minimum number of operational links k out of n links, a user is simultaneously connected to. We derive closed form expressions for the case of Selection Combining of n Rayleigh fading links, equivalent to $1\text{oo}n$.

A. Channel Availability

According to [13], "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 the basis of this definition the following availability quantities can be derived with respect to the wireless channel.

The *instantaneous channel availability*

$$A(t) = \Pr\{Y(t) = 1\} \tag{7}$$

is the probability that a channel is operational at a given instant of time t. The *steady-state channel availability*

$$A = \lim_{t\to\infty} A(t) \ , \tag{8}$$

characterizes the long-term probability that one channel is operational. The steady-state channel availability can also be interpreted as the mean proportion of time the channel is operational.

We can apply the concept of availability to the introduced scenario, because the considered wireless communications system is available if it is in one of the system up states aggregated in $\mathcal{U}$. The steady-state situation is often of special interest to make conclusions about the system's long-term performance. Thus, we determine the system steady-state channel availability as

$$A_{k,n} = \sum_{j\in\mathcal{U}} P_j = \sum_{j=k}^{n} P_j \ . \tag{9}$$

The steady-state probabilities $\boldsymbol{P} = [P_0, P_1, \ldots, P_n]$ satisfy the matrix equation $\boldsymbol{P} \cdot \boldsymbol{M} = [0, 0, \ldots, 0]$.

Since the considered system model is a birth-death Markov process, the steady-state probabilities can be computed by [6]

$$P_j = \frac{\prod\limits_{i=0}^{j-1} \left(\dfrac{\mu_i}{\lambda_{i+1}}\right)}{1 + \sum\limits_{\ell=1}^{n} \prod\limits_{m=0}^{\ell-1} \left(\dfrac{\mu_m}{\lambda_{m+1}}\right)} \tag{10}$$

for $j = 0, 1, \ldots, n$. We apply the transition rates (6) according to the introduced wireless communications system scenario, obtaining

$$P_j = \frac{n!}{j!(n-j)!\rho^j} \left(1 + \sum_{\ell=1}^{n} \frac{n!}{\ell!(n-l)!\rho^\ell}\right)^{-1} \tag{11}$$

with the ratio

$$\rho = \lambda/\mu = \exp\left(\frac{1}{F}\right) - 1 \ . \tag{12}$$

It is obvious that, for the considered wireless communications system scenario, the steady-state probabilities and consequently the user's steady-state channel availability purely depend on the fading margin F. Hence, this metric does not reflect the influence of mobility aspects or the carrier frequency on the communication performance.

The complement of the steady-state channel availability $A_{k,n}$ characterizes the outage probability given by

$$P_{\mathrm{out},k,n} = 1 - A_{k,n} = \sum_{j\in\mathcal{D}} P_j = \sum_{j=0}^{k-1} P_j \ . \tag{13}$$

It corresponds to the packet loss rate (PLR), a quantity often used to specify reliability requirements in communications systems, because it can be interpreted as the long-term probability that the communications system is not operational. The special case $k = 1$ leads to the steady-state channel availability of selection combined Rayleigh fading links

$$A_{1,n} = 1 - \frac{\lambda^n}{(\lambda+\mu)^n} = 1 - \left(1 - \exp\left(-\frac{1}{F}\right)\right)^n \tag{14}$$

confirming the known probability expression [11].

B. Mean Time Between Failures

The mean time between system failures (MTBF) is the mean time between consecutive transitions from an up state to a down state [14]. We apply this definition to the considered wireless communications scenario. Based on the frequency of system failures

$$\omega_{k,n} = \sum_{i\in\mathcal{U}}\sum_{\ell\in\mathcal{D}} P_i \cdot a_{i\ell} \tag{15}$$

the $\mathrm{MTBF}_{k,n}$ for a user requesting $k$oo$n$ links is determined as

$$\mathrm{MTBF}_{k,n} = \frac{1}{\omega_{k,n}} \tag{16}$$

where $a_{i\ell}$ denotes the transition rate from state i to ℓ [14]. For n selection combined Rayleigh fading links, this simplifies to

$$\mathrm{MTBF}_{1,n} = \frac{1}{\lambda P_1} = \frac{(\lambda+\mu)^n}{n\mu\lambda^n} \tag{17}$$

due to the birth-death structure of the considered system model applying the steady-state probability (10) with $k = 1$. It it obvious that this can be written as

$$\mathrm{MTBF}_{1,n} = \frac{1}{n\mu P_{\mathrm{out},1,n}} \ , \tag{18}$$

utilizing equations (14) and (13). We derive the closed form expression

$$\mathrm{MTBF}_{1,n} = \frac{\exp\left(\frac{1}{F}\right) - 1}{n f_{\mathrm{D}}\sqrt{\frac{2\pi}{F}}\left(1-\exp\left(\frac{-1}{F}\right)\right)^n} \tag{19}$$

by inserting the transition rates (2).

C. Mean Down Time

The *mean down time* (MDT) identifies the mean duration of a system failure, defined as the mean time from when the system enters a down state until it is repaired and transitions back to an up state [14]. This is an essential metric to make conclusions about a system's capability to self-repair/recover after a failure. The outage probability $P_{\mathrm{out},k,n}$ is equal to the frequency $\omega_{k,n}$ of system failures multiplied by the mean down time $\mathrm{MDT}_{k,n}$. Applied to the introduced scenario, the mean down time $\mathrm{MDT}_{k,n}$ from a user's viewpoint, requesting at least k operational links, can be calculated as

$$\mathrm{MDT}_{k,n} = \frac{1 - A_{k,n}}{\omega_{k,n}} \ . \tag{20}$$

Selection combing of n Rayleigh fading links yields

$$\mathrm{MDT}_{1,n} = \frac{1}{n\mu} \ , \tag{21}$$

employing the steady-state availability expression (14) and equation (17). By substituting the transition rates (2), we determine the closed form expression

$$\mathrm{MDT}_{1,n} = \frac{\exp\left(\frac{1}{F}\right) - 1}{n f_{\mathrm{D}}\sqrt{\frac{2\pi}{F}}} \ , \tag{22}$$

which is independent of the failure rate λ because the MDT only considers down times, i.e., all channels are failed and a single channel repair leads to a system repair. Thus, the failures and the corresponding failure rates are irrelevant.

D. Mean Up Time

The *mean up time* (MUT) characterizes the mean system operational time until a failure occurs. Applied to the considered scenario, it is defined as the mean time from a transition to an up state until the first transition back to a down state. Using the relation

$$\mathrm{MTBF}_{k,n} = \mathrm{MUT}_{k,n} + \mathrm{MDT}_{k,n} \ , \tag{23}$$

we obtain the mean up time $\mathrm{MUT}_{k,n}$ for a user requesting at least k operational links by

$$\mathrm{MUT}_{k,n} = \frac{A_{k,n}}{\omega_{k,n}} \ . \tag{24}$$

In the special case of n selection combined Rayleigh fading links we insert equations (14) and (17) obtaining

$$\mathrm{MUT}_{1,n} = \frac{(\lambda+\mu)^n}{n\mu\lambda^n} - \frac{1}{n\mu} \ . \tag{25}$$

Applying the transition rates (2) yields the closed form expression given by

$$\mathrm{MUT}_{1,n} = \frac{\exp\left(\frac{1}{F}\right) - 1}{n f_{\mathrm{D}}\sqrt{\frac{2\pi}{F}}}\left(\frac{1}{\left(1-\exp\left(\frac{-1}{F}\right)\right)^n} - 1\right) \ . \tag{26}$$

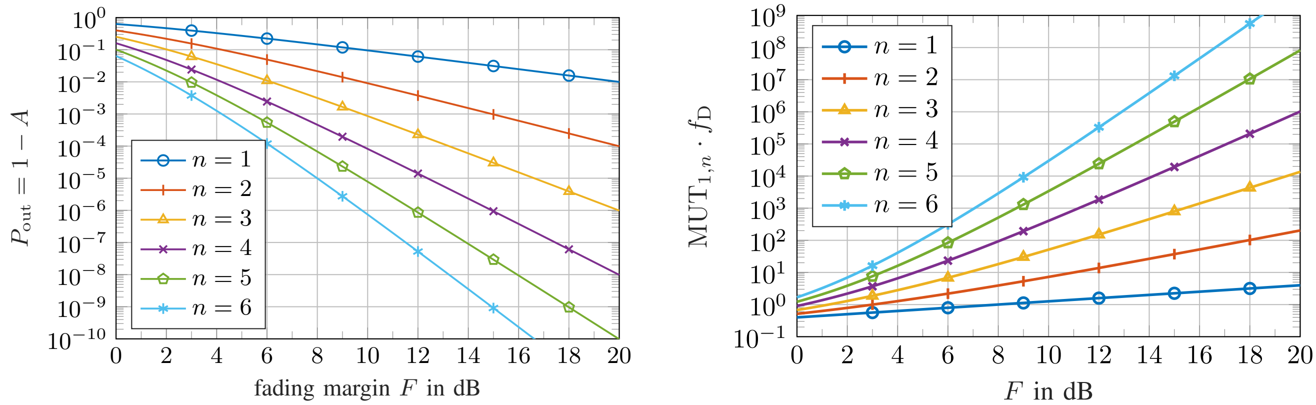
It turns out that, in contrast to the steady-state channel availability $A_{k,n}$, the user's $\mathrm{MTBF}_{k,n}$, $\mathrm{MDT}_{k,n}$, and $\mathrm{MUT}_{k,n}$ depend on the fading margin F and maximum Doppler shift f_{D}. Hence, we propose to utilize these KPIs for the research on wireless communications systems, because these metrics enable to evaluate the reliability of the wireless communications system from the user's viewpoint taking into account the actual rates λ and μ. It is obvious that system reliability is based upon the quantities $\mathrm{MUT}_{k,n}$, $\mathrm{MDT}_{k,n}$, and $\mathrm{MTBF}_{k,n}$ besides channel availability, which can be linked by the following relation

$$A_{k,n} = \frac{\mathrm{MUT}_{k,n}}{\mathrm{MTBF}_{k,n}} \ . \tag{27}$$

IV. Evaluation Scenario and Results

In this section, the considered reliability metrics are evaluated for the exemplary scenario 1oo6, i.e., $n = 6$ and $k = 1$ is selected. This relates to the considered wireless communications scenario by assuming that data is sent redundantly over $n = 6$ links, to which a user is connected, and the user performs Selection Combining, corresponding to $k = 1$.

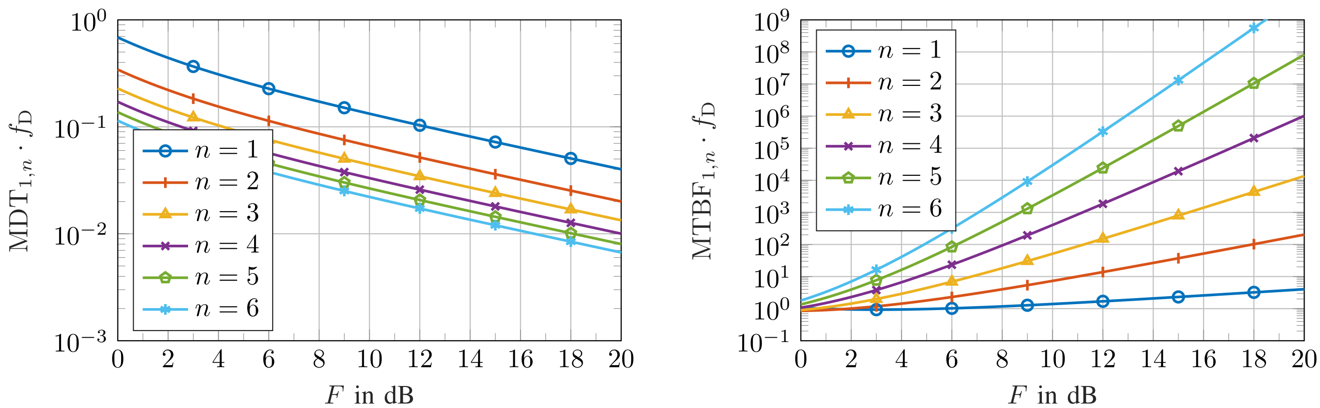
Evaluations of the steady-state channel availability $A_{1,n}$ are shown for different values of F and n in Fig. 2(a). Higher degrees of redundancy, which are equivalent to higher values of n, increase the steady-state channel availability. The differences increase for larger fading margins F. Hence, introducing redundancy improves availability, especially for small values of F. Interpreting outage probability $P_{\mathrm{out},1,n} = 1 - A_{1,n}$ as PLR, as assumed in this paper, enables system design recommendations for a given fading margin F. For example in this scenario, it is not possible to achieve a $\mathrm{PLR} < 10^{-9}$



(a) Steady-state channel availability.

(b) Mean up time.

Fig. 2. Steady-state channel availability and mean up time for selection combined Rayleigh fading links and varying values of F and n.



(a) Mean down time.

(b) Mean time between failures.

Fig. 3. MDT and MTBF, for selection combined Rayleigh fading links and varying values of F and n.

TABLE I
EXEMPLARY COMPARISON OF MUT, MDT AND OUTAGE PROBABILITY OF n SELECTION COMBINED LINKS FOR $F = 20\,\text{dB}$

n	$P_{\text{out},1,n}$	v [m/s]	f [GHz]	$\text{MDT}_{1,n}$	$\text{MUT}_{1,n}$
3	10^{-6}	10	2	0.2 ms	3.4 min
3	10^{-6}	10	60	6.7 μs	6.8 s
3	10^{-6}	80	2	25.0 μs	25.4 s
3	10^{-6}	80	60	0.8 μs	0.8 s
5	10^{-10}	10	2	0.1 ms	14.3 d
5	10^{-10}	10	60	4.0 μs	11.4 h
5	10^{-10}	80	2	15.0 μs	42.8 h
5	10^{-10}	80	60	0.5 μs	1.4 h

for a user connected to 4 links simultaneously and the plotted range of F.

Furthermore, it is of key importance to also consider the metrics $\text{MUT}_{1,n}$, $\text{MDT}_{1,n}$, $\text{MTBF}_{1,n}$ leading to a joint analysis of availability and reliability. In contrast to steady-state channel availability and outage probability, these quantities depend on the maximum Doppler shift f_{D}, reflecting the impact of the carrier frequency and mobility aspects. We normalize the metrics by f_{D} and present numerical results in Figs. 2(b), 3(a), and 3(b), respectively. As shown in Fig. 2(b), the $\text{MUT}_{1,n}$ is higher for larger values of n. The differences increase for larger values of F for a given f_{D}. In contrast to the $\text{MUT}_{1,n}$, the $\text{MDT}_{1,n}$ focuses on the down times, see Fig. 3(a). The $\text{MDT}_{1,n}$ decreases for larger values of F for a selected f_{D}. A higher degree of redundancy, corresponding to a higher n, implies a shorter $\text{MDT}_{1,n}$. The gaps between different levels of redundancy n remain constant, regardless of the fading margin F since the $\text{MDT}_{1,n}$ linearly depends on the number of links n. In Fig. 3(b), we evaluate the $\text{MTBF}_{1,n}$ statistics. Most importantly, it cannot be determined whether a high value of $\text{MTBF}_{1,n}$ corresponds to high a $\text{MUT}_{1,n}$ or a high $\text{MDT}_{1,n}$, because the $\text{MTBF}_{1,n}$ is the sum of $\text{MDT}_{1,n}$ and $\text{MUT}_{1,n}$. Therefore, only investigating $\text{MTBF}_{1,n}$ values may lead to confusion. For the considered evaluation scenario the $\text{MTBF}_{1,n}$ is dominated by $\text{MUT}_{1,n}$.

After analyzing the different metrics individually, we subsequently study them jointly. Several cases with different values for the carrier frequency f and velocity v may all lead to the same steady-state channel availability $A_{1,n}$. In Table I, we evaluate combinations of low and high velocity v with different carrier frequencies f for $n = 3$ and $n = 5$ redundant links, confining our concentration on the exemplary fading margin $F = 20\,\mathrm{dB}$. Obviously, multiple system designs with the same outage probability $P_{\mathrm{out},1,n}$ can exhibit significantly varying $\mathrm{MUT}_{1,n}$ and $\mathrm{MDT}_{1,n}$. For $n = 3$ links the obtained outage probability $P_{\mathrm{out},1,n} = 10^{-6}$ appears promising for many URLLC use cases, but the $\mathrm{MUT}_{1,3}$ differs by orders of magnitude in the range between $800\,\mathrm{ms}$ and $3.4\,\mathrm{min}$. The corresponding $\mathrm{MDT}_{1,3}$ values are comparable to latency requirements for URLLC applications, e.g., wireless factory automation. Thus, it is obvious that the reliability requirements cannot be permanently satisfied if the MDT is in the range of the latency constraints, even though current systems should be able to tolerate short down times. As expected, two additional redundant links improve the outage probability $P_{\mathrm{out},1,5}$ by a factor of 10,000. The $\mathrm{MUT}_{1,5}$ also increases significantly, the expected up time of more than two weeks for the low mobility and low frequency scenario could be similar to the maintenance cycle in factory automation. However, the $\mathrm{MDT}_{1,5}$ is not even reduced by half.

Consequently, the reliability metrics MDT and MUT can give an estimate whether a system supports particular use cases or not. This can be extended by aiming for concrete performance guarantees, requiring to study the detailed distributions of up and down times. As real system-data is necessary for these distributions, this is out of the scope of this work. Another conclusion is that only jointly studying availability and reliability enables proper system analysis and design as shown in Table I.

V. Summary

Jointly designing reliable systems from different domains is a major cornerstone for realizing URLLC. In order to successfully introduce wireless communications systems, e.g., to factory automation, it is important to use a common performance evaluation methodology. In this work, we presented fundamental definitions and derived additional relations between them to put forward a solid foundation for joint discussions and studies. As demonstrated in this work, it is possible and beneficial to leverage the existing toolset of reliability theory, based on which the life cycles and failures of communication networks can be analyzed and improved. We obtained closed form expressions of the time-based reliability metrics MUT, MDT, and MTBF concentrating on the special case of Selection Combining of multiple Rayleigh fading links. Supported by numerical examples, we discussed the trade-off between the number of links used for multi-connectivity, fading margin, velocity, and carrier frequency with respect to channel availability, and time-based reliability metrics. It is demonstrated that a combined evaluation of availability and reliability metrics is of key importance. Only considering either availability or reliability can cause to misleading conclusions and results. Additionally, latency requirements need to be taken into account as well. It has been shown that utilizing KPIs like MUT, MDT, MTBF besides availability refines the discussion on reliability in 5G networks.

All in all, the results at hand can help mastering key challenges of future networks, which aim to support unprecedented, new use cases of URLLC. For future work, we propose to use empirical data from communication networks to derive detailed statistical parameters, which, in turn, serve as inputs for the analytical evaluation tool presented. Moreover, the models presented need to be extended to studies of detailed quantiles of probability distributions, in order to give concrete performance guarantees.

Acknowledgment

This work was supported by the project “fast automation” and the Federal Ministry of Education and Research of the Federal Republic of Germany (BMBF) within the initiative “Region Zwanzig20” under project number 03ZZ0510F.

References

[1] Nokia, “5G use cases and requirements,” *White paper*, 2016.
[2] M. Simsek, A. Aijaz, M. Dohler, J. Sachs, and G. P. Fettweis, “5G-Enabled Tactile Internet,” *IEEE Journal on Selected Areas in Communications*, vol. 34, no. 3, pp. 460–473, March 2016.
[3] 3GPP TR 38.913 V14.3.0, “Study on scenarios and requirements for next generation access technologies,” *Technical Report*, June 2017.
[4] P. Schulz, M. Matthe, H. Klessig, M. Simsek, G. P. Fettweis, J. Ansari, S. A. Ashraf, B. Almeroth, J. Voigt, I. Riedel, A. Puschmann, A. Mitschele-Thiel, M. Müller, T. Elste, and M. Windisch, “Latency Critical IoT Applications in 5G: Perspective on the Design of Radio Interface and Network Architecture,” *IEEE Communications Magazine*, vol. 55, no. 2, pp. 70–78, February 2017.
[5] M. Simsek, D. Zhang, D. Öhmann, M. Matthé, and G. P. Fettweis, “On the flexibility and autonomy of 5G wireless networks,” *IEEE Access*, vol. 5, pp. 22 823–22 835, June 2017.
[6] K. S. Trivedi, *Probability and Statistics with Reliability, Queuing and Computer Science Applications*, 2nd ed. Chichester: Wiley, 2016.
[7] T. Hößler, L. Scheuvens, N. Franchi, M. Simsek, and G. P. Fettweis, “Applying reliability theory for future wireless communication networks,” in *2017 IEEE 28th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*, October 2017, pp. 1–7.
[8] I. A. M. Balapuwaduge, F. Y. Li, and V. Pla, “System times and channel availability for secondary transmissions in CRNs: A dependability-theory-based analysis,” *IEEE Transactions on Vehicular Technology*, vol. 66, no. 3, pp. 2771–2788, March 2017.
[9] E. N. Gilbert, “Capacity of a burst-noise channel,” *The Bell System Technical Journal*, vol. 39, no. 5, pp. 1253–1265, September 1960.
[10] M. Zorzi, R. R. Rao, and L. B. Milstein, “On the accuracy of a first-order markov model for data transmission on fading channels,” in *1995 Fourth IEEE International Conference on Universal Personal Communications*, November 1995, pp. 211–215.
[11] D. Öhmann and G. P. Fettweis, “Minimum duration outage of wireless rayleigh-fading links using selection combining,” in *2015 IEEE Wireless Communications and Networking Conference (WCNC)*, March 2015, pp. 681–686.
[12] W. Kuo and M. J. Zuo, *Optimal Reliability Modeling: Principles and Applications*. Hoboken: Wiley, 2003.
[13] ITU-T, “Recommendation E.800: Quality of service and dependability vocabulary,” 2008.
[14] A. Høyland and M. Rausand, *System Reliability Theory: Models and Statistical Methods*. Wiley, 2009.