Mission Reliability for URLLC in Wireless Networks

Tom Hößler, Meryem Simsek, and Gerhard P. Fettweis

***Abstract*—Achieving connectivity reliability for Ultra-Reliable Low-Latency Communication (URLLC) is one major challenge for future wireless communications systems. The current understanding of reliability does not sufficiently cover time-related aspects, e.g, time-varying channels or the duration of a certain condition in a wireless system. Moreover, different applications require diverse execution periods during which no failure is allowed, which we denote as *mission duration*. In this paper, we focus on time-related aspects and introduce the performance metric *mission reliability* to wireless communications systems and employ its connection to the *mean time to first failure* (MTTFF), reflecting the expected time until the first failure occurs. As diversity is accepted to be essential for reliability, their evaluation is presented regarding a multi-connectivity system with Rayleigh fading, reflecting frequency diversity. We demonstrate the trade-off between mission duration, mission reliability, and the number of links used for multi-connectivity, which can stimulate the discussion on URLLC and advance the design of future wireless systems.**

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

I. Introduction

One of the most challenging use cases, which the fifth generation (5G) of mobile communications systems addresses, is Ultra-Reliable Low-Latency Communication (URLLC) enabling, e.g., wireless factory automation, coordination among vehicles, and real-time remote control in the Tactile Internet [1], [2]. Within the context of 5G, key performance indicators (KPIs) such as "availability" and "reliability" are often used interchangeably and in a colloquial way [3], [4]. The targeted optimum of zero mobility interruption is the only explicit time attribute in the current discussion on reliability in 5G [5]. Leveraging well accepted definitions and methods of reliability theory to wireless channels with respect to time aspects has been addressed only by a few researchers: The expected reliability and the mean time to first failure (MTTFF) of a wireless system with imperfect components are analyzed in [6]. However, perfect communication links are assumed. In [7], concepts of reliability theory are applied and extended to wireless communications networks, which are modeled as repairable systems with co-channel interference as cause of failures. Another availability and reliability analysis of wireless channels is performed in [8], restricted to cognitive radio networks. It is obvious that further research activities should be performed linking reliability theory and wireless communications. The common definition of reliability in wireless systems as the percentage of successfully delivered data within a certain deadline is equivalent to packet loss rate [3]. However, this definition does neither reflect the time dependence of time-varying wireless channels nor different time duration required for URLLC services. Since current KPIs do not cover these requirements, this paper discusses the performance analysis within a given time interval, denoted as mission duration, during which no communication failure is allowed. Inspired by classical reliability theory, we introduce the concept of mission reliability as the probability of achieving this requirement as a main contribution of this paper and utilize the metric MTTFF, i.e., the expected mission duration without any failure, in wireless communications systems. In order to demonstrate their benefits, we model a wireless communications system as a repairable system based on the analytical method of continuous-time Markov chains (CTMCs) focusing on Rayleigh fading as a main cause of failure. Since diversity is widely accepted to be key to compensate for fades and increase reliability, we concentrate on frequency diversity and study the impact of multi-connectivity on the introduced KPIs. Further contributions of this paper comprise the presentation of a closed form expression of MTTFF, and the determination of a mission reliability approximation for multiple selection combined links. By evaluating an exemplary scenario, the trade-off between mission duration, mission reliability and the number of links required is discussed.

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All authors are with the Vodafone Chair Mobile Communications Systems, Technische Universität Dresden, Dresden, Germany, Emails: {tom.hoessler, meryem.simsek, gerhard.fettweis}@tu-dresden.de.

M. Simsek is also with the International Computer Science Institute, Berkeley, USA, Email: simsek@icsi.berkeley.edu.

II. System Model

We consider a single user connected to n wireless links simultaneously and focus on multi-path propagation as a cause of failure. Assuming that each wireless link consists of multiple paths without a dominant component leads to a Rayleigh-fading channel. We assume the links to be separated in frequency at least by the coherence bandwidth resulting in independent fading. Data is sent redundantly over each link. The user performs Selection Combining, i.e., the best link out of n links is selected. Thus, it is sufficient if at least one link is operational. Path loss and shadowing are not considered in this paper, because we assume compensation by transmit power control or automatic gain control according to [9]. However, these assumptions are not essential, and the proposed metrics can be applied to wireless systems including path loss and shadowing.

A. Single Rayleigh-Fading Link

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. 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 [10], [11]. Thus, we distinguish between two states by introducing the random variable channel state

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

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 (see [9]):

$$\lambda = \sqrt{\frac{2\pi}{F}} f_{\mathrm{D}} , \qquad \mu = \frac{\sqrt{\frac{2\pi}{F}} f_{\mathrm{D}}}{\exp \frac{1}{F} - 1} , \quad (2)$$

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 by 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. Furthermore, the system investigated in this paper is based on the following assumptions. Every fading is self-revealing, i.e., 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. Since the presented analysis is based on the transition rates in (2), the extension to general fading channels (e.g., Rician [12]) is possible by determining and incorporating the corresponding expressions of failure and repair rates.

B. Multiple Rayleigh-Faded Links

We extend the introduced channel model to n independent, selection combined links and translate the resulting repairable system to an irreducible, homogeneous CTMC. Let the finite system state j reflect the number of operational channels. The system state j is decreased by one whenever a channel fails and increased by one when a failed channel is operational again. The state space is partitioned into the set of operational states $\mathcal{U} = \{1, 2, \ldots, n\}$ and the set of failed states $\mathcal{D} = \{0\}$. The resulting birth-death CTMC is visualized in Fig. 1. The balance equations are expressed by

$$\dot{P}_j(t) = \mu_{j-1} P_{j-1}(t) - (\lambda_j + \mu_j) P_j(t) + \lambda_{j+1} P_{j+1}(t) \quad \text{for } j = 0, 1, \ldots, n , \quad (3)$$

where $P_j(t)$ is the state probability that j channels in the system are operational 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 $j > n$. Throughout the paper, we assume the links to be independent with equal fading margin F and maximum Doppler shift f_{D}. Thus, the system transition parameters of the considered wireless communications scenario result in

$$\lambda_j = j\lambda \qquad \text{for } 0 < j \leq n , \quad (4a)$$

$$\mu_j = (n-j)\mu \quad \text{for } 0 \leq j < n . \quad (4b)$$

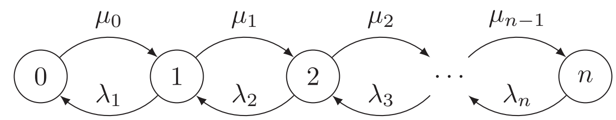

Fig. 1. Birth-Death CTMC

This model reduces to a non-diversity system for $n = 1$.

III. Performance Metrics

In this section, we introduce and compare performance metrics to evaluate URLLC systems. The definitions are applied to selection combined Rayleigh-faded links.

A. Channel Availability

According to reliability theory, an item is called 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 predefined time interval, assuming that the external resources, if required, are provided [13]. We apply this definition to wireless communications by referring to the fundamental requirement of an operational channel and introduce the performance metric *instantaneous channel availability* of a single link as the probability to be operational at a certain time instant t according to $A_1(t) = \Pr\{Y(t) = 1\}$. The instantaneous channel availability of the considered diversity system with n links $A_n(t) = \sum_{j \in \mathcal{U}} P_j(t) = \sum_{j=1}^{n} P_j(t)$ corresponds to the probability of being in the set of operational states $\mathcal{U}$ at time instant t.

The *steady-state channel availability* $A_n = \lim_{t \to \infty} A_n(t)$ can be interpreted as the mean proportion of time when communication is possible [7]. Thus, the sum of the overall outage probability and the steady-state channel availability equals one. Based on the introduced CTMC, the steady-state channel availability of selection combined Rayleigh fading links is derived as

$$A_n = 1 - \frac{\lambda^n}{(\lambda + \mu)^n} = 1 - \left(1 - \exp\left(-\frac{1}{F}\right)\right)^n . \quad (5)$$

This confirms the known outage probability expression for selection combined Rayleigh-faded links [9]. Obviously, the steady-state channel availability only depends on the fading margin F. Hence, this metric cannot reflect the influence of mobility aspects or the carrier frequency on the communication performance.

B. Mission Reliability

According to [13], reliability is defined as the probability that an item can perform a required function under stated conditions for a given time interval. Thus, demanding a certain reliability value without specifying the corresponding time interval is not a valid statement. We denote this time interval as "mission" of length Δt and define the performance metric *mission reliability* as

$$R_1(\Delta t) = \Pr\{Y(\tau) = 1 \, \forall \, \tau \in [0, \Delta t]\} \quad (6)$$

emphasizing the reference to failure-free operation throughout the mission. Mission reliability fundamentally differs from the

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reliability definition by 3GPP, which is the mean proportion of time, in which packets are successfully delivered [3]. Hence, the 3GPP interpretation corresponds to the concept of steady-state channel availability.

In order to determine the mission reliability of the considered wireless communications system, the introduced CTMC is modified by assuming failed states to be absorbing. Thus, the differential balance equations retain the same structure as in eq. (3). The corresponding transition rates in (2) remain also the same, except for $\mu_0 = 0$. The state probabilities $\hat{P}_j(\Delta t)$ of the modified Markov model denote the probability that j channels are operational at the end of mission duration Δt and that the number of operational channels has never reached zero during the mission duration Δt. The mission reliability

$$R_n(\Delta t) = \sum_{j \in \mathcal{U}} \hat{P}_j(\Delta t) = \sum_{j=1}^{n} \hat{P}_j(\Delta t) \tag{7}$$

characterizes the probability of not leaving the set of operational states $\mathcal{U}$ during the mission duration Δt. In general, the mission reliability $R_n(\Delta t)$ is a time dependent function converging to zero. In the considered system model, the maximum Doppler frequency f_D purely acts as a scaling factor to the mission duration Δt, yielding $R_n = g(f_\mathrm{D}\Delta t)$, since the maximum Doppler frequency f_D is a factor in both the transition rates (2) and the balance equations (3).

C. Mean Time to First Failure

The *mean time to first failure* (MTTFF) is closely related to mission reliability. This scalar characterizes the average duration an item will operate before the first failure occurs. MTTFF is a fundamental and well-accepted metric in reliability analysis of technical systems, plant facilities, electronic equipment, hardware devices, individual components etc. However, this KPI has not yet prevailed in the discussion on wireless links. Hence, we utilize MTTFF as a promising KPI in the context of wireless communications systems, because this quantity enables reliability analysis comprising time aspects, which are of particular importance for URLLC. The MTTFF for n selection combined links can be determined using an infinite integral or Laplace transform $R_n^*(s)$ of the corresponding mission reliability function and setting the Laplace parameter $s = 0$ [14],

$$\mathrm{MTTFF}_n = \int_0^\infty R_n(\tau)\,\mathrm{d}\tau = R_n^*(0) = \sum_{j=1}^{n} \hat{P}_j^*(0)\ . \tag{8}$$

In order to determine the Laplace transformation of the state probabilities $\hat{P}_j^*(0)$ of the modified Markov model, we utilize the Laplace transform of the respective balance equations

$$\mu_{j-1}P_{j-1}^*(0) - (\lambda_j + \mu_j)P_j^*(0) + \lambda_{j+1}P_{j+1}^*(0) = -\hat{P}_j(0) \tag{9}$$

for $j = 1, 2, \ldots, n$. Assuming all n channels to be operational at time $t = 0$, equivalent to $\hat{P}_n(0) = 1$ and $\hat{P}_j(0) = 0$ for $j \neq n$, we obtain $\hat{P}_1^*(0) = 1/\lambda$ and

$$\hat{P}_j^*(0) = \frac{1}{\lambda_j}\left((\lambda_{j-1} + \mu_{j-1})\hat{P}_{j-1}^*(0) - \mu_{j-2}\hat{P}_{j-2}^*(0)\right) \tag{10}$$

for $1 < j \leq n$ with $\hat{P}_j^*(0) \equiv 0$ otherwise. We present a closed form expression of the MTTFF for n selection combined links

$$\mathrm{MTTFF}_n = \frac{1}{\lambda}\sum_{j=1}^{n} \frac{\sum\limits_{g=1}^{j} \rho^{g-1}(g-1)! \prod\limits_{\ell=g}^{j-1}(n-\ell)}{\rho^{j-1} j!} \tag{11}$$

by inserting the transition rates from eq. (2) to eq. (10), resolving its recursive structure, and applying eq. (8). The term $\rho = \lambda/\mu = \exp(1/F) - 1$ characterizes the ratio of failure rate and repair rate.

Please, note that in contrast to the steady-state channel availability A_n, the MTTFF_n takes the carrier frequency and mobility into account, because it depends on the fading margin F and the maximum Doppler frequency f_D. The relationship between the MTTFF_n and the failure rate λ or the maximum Doppler frequency f_D remains inversely proportional, independent of the number of links.

IV. Mission Reliability Approximation

The complexity of deriving the mission reliability increases with the number of links, because it requires solving the differential balance equation system (9). The mission reliability of the single-connectivity, i.e., $n = 1$, results in $R_1(\Delta t) = \exp(-\Delta t/\mathrm{MTTFF}_1)$ with $\mathrm{MTTFF}_1 = 1/\lambda$. This complies with the fact that the time to failure of a single item with constant failure rate λ is exponentially distributed [14]. Based on this result, we model the considered diversity system as a single item and propose the approximation

$$\tilde{R}_n(\Delta t) = \exp\left(\frac{-\Delta t}{\mathrm{MTTFF}_n}\right) \tag{12}$$

with the constant failure rate $1/\mathrm{MTTFF}_n$ determined from the closed form expression (11).

V. Evaluation

In this section, we evaluate the proposed performance metrics with respect to an exemplary scenario comprising a typical fading margin $F = 20\,\mathrm{dB}$ [15], medium velocity $v = 10\,\mathrm{m/s}$, and the carrier frequency $f = 2\,\mathrm{GHz}$, equivalent to $f_\mathrm{D} = 66.6\,\mathrm{Hz}$, if not stated otherwise. All n channels are assumed to be operational at time $t = 0$.

In Fig. 2, we focus on the special case of single-connectivity $n = 1$ presenting fundamental differences between channel availability and mission reliability. The instantaneous channel availability $A_1(t)$ converges quickly to the steady-state channel availability $A_1 = 0.99$. Thus, in the steady state, an outage probability of $1\,\%$ is expected at any instant of time. On the other hand, the mission reliability $R_1(\Delta t)$ approaches zero, because a failure-free operation is practically impossible for long missions due to the random fading process. Hence, in the context of URLLC with different mission duration it is necessary to analyze and improve the mission reliability and the MTTFF of wireless communication channels.

Fig. 3 shows the impact of multi-connectivity on the MTTFF for $n > 1$. As expected, the MTTFF_n increases with growing numbers of links n and fading margin F, respectively.

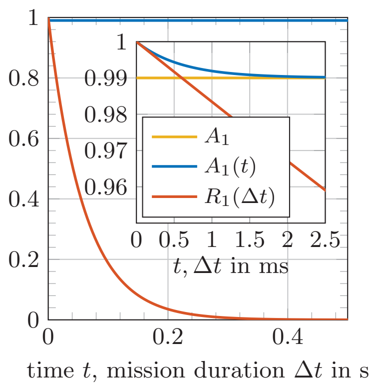

Fig. 2. Instantaneous channel availability, steady-state channel availability, and mission reliability for a single Rayleigh-fading link, $f_{\mathrm{D}} = 66.6\,\mathrm{Hz}$, $F = 20\,\mathrm{dB}$.

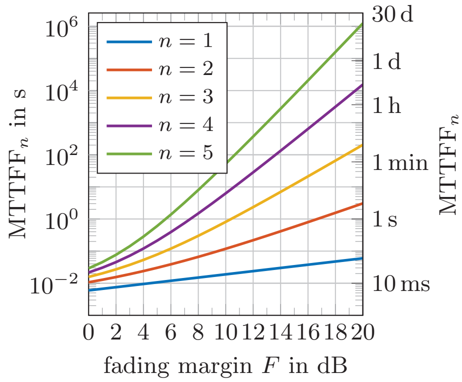

Fig. 3. MTTFF for n selection combined Rayleigh-fading links, $f_{\mathrm{D}} = 66.6\,\mathrm{Hz}$.

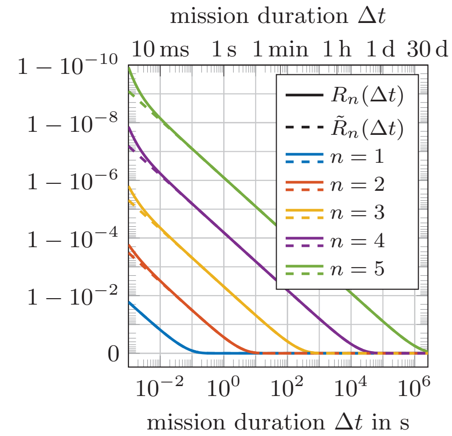

Fig. 4. Mission reliability and corresponding approximation for n selection combined Rayleigh-fading links, $f_{\mathrm{D}} = 66.6\,\mathrm{Hz}$, $F = 20\,\mathrm{dB}$.

However, for a single link even with a fading margin of $F = 20\,\mathrm{dB}$ the average time until the first failure occurs is below $100\,\mathrm{ms}$, which is too short for many use cases: For instance, the mission duration of an autonomous car crossing an intersection is about $10\,\mathrm{s}$. In order to achieve a similar MTTFF, a fading margin of $F > 15\,\mathrm{dB}$ and three links are required. A MTTFF of 30 days, which may correspond to a maintenance cycle in factory automation, can be realized by $n = 5$ links with fading margin $F \geq 20\,\mathrm{dB}$.

In Fig. 4, we analyze the accuracy of our proposed approximation (12) by comparing it to the mission reliability resulting from equation (7). It is clearly visible that the approximation $\tilde{R}_n$ is a lower bound for the mission reliability R_n and for mission duration $\Delta t > 10\,\mathrm{ms}$ the approximation shows a very good match. Fig. 4 reveals the trade-off between mission duration, mission reliability, and number of links, which can be applied to specify requirements for URLLC. In contrast to existing KPIs, we can define the performance threshold by a target mission duration and the corresponding mission reliability. For instance, if a mission reliability of more than $99.999\,\%$ is required for an autonomous car throughout the mission of $10\,\mathrm{s}$ crossing an intersection, at least $n = 5$ selection combined links are necessary.

VI. Conclusion

In this paper, we introduced the mission reliability and employed the closely related MTTFF to wireless communications systems. Utilizing these performance metrics will carry the discussion on URLLC to a new stage, because these metrics link the dimensions reliability and time. A multi-connectivity system with Rayleigh fading has been analytically modelled and evaluated based on CTMCs. We determined a mission reliability approximation for multiple selection combined links. Our proposed expression for the MTTFF of a diversity system has a closed form without the need for differential equation systems, infinite integrals, or Laplace transformation. We have demonstrated that the trade-off between mission reliability, mission duration, and the number of links used for multi-connectivity has the potential to refine requirements and advance the design of future wireless systems. Based on this work wireless channels can be modeled as components of a technical system to improve the overall reliability, which is key to realize URLLC applications in 5G.

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