Dynamic Connectivity for Robust Applications in Rayleigh-Fading Channels

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***Abstract*—The fifth generation (5G) of mobile networks envisions ultra-reliability in wireless communications. One common approach to guarantee that is diversity, e.g., by sending data redundantly over several channels to prevent the interruption of the combined signal. However, many applications, which we refer to as robust, are able to tolerate short communication outages. Thus, we propose a dynamic connectivity scheme named "reaction diversity", which only switches the channel in case of bad conditions, instead of providing multiple channels throughout the transmission. As a result, time-correlated failures, e.g., caused by fading, are shortened. Through simulations with Rayleigh fading channels, we show that if short outages are acceptable, the application outage probability can be reduced by several orders of magnitude over selection combining of two channels, while only consuming half the resources.**

***Index Terms*—5G, Application outage probability, Reaction diversity, URLLC**

I. INTRODUCTION

Achieving wireless ultra reliable low latency communications (URLLC) is one of the main challenges in the fifth generation (5G) of wireless communication systems and beyond. A latency in the (sub-)millisecond range together with ultra-high reliability is expected to enable wireless factory automation and self-driving cars, among other services; and real-time remote control, which will pave the way to the Tactile Internet [1]. In URLLC, packet delivery success probabilities of $1-10^{-5}$ up to $1-10^{-9}$ are targeted [2], [3]. Although any wireless communications system suffers from signal fluctuations over time, referred to as fading, the analysis of time-based dependability attributes is still lacking in the context of URLLC. Fortunately, many modern applications, such as robotics, can tolerate short communication outage times due to appropriate mechanisms in the application domain, e.g., fault-tolerant controllers [4]. We name these wireless systems with applications that are not sensitive to short outages robust. This potential can be leveraged for the design of the wireless communications system, since the importance of a packet for the application depends on the success or failure of immediately preceding packet transmissions. Hence, taking the duration of failures into account is gaining interest in the area of wireless communications systems: Related concepts comprise "survivability", "minimum duration outage", and "mission availability" [5]–[7]. However, existing static diversity schemes are not able to dynamically react to instantaneous failures and therefore waste resources that are not needed for a smooth operation [4].

In this letter, we propose a novel dynamic connectivity concept, namely *reaction diversity (RD)*, which reacts to fades by selecting a different channel. We study the outage probability of robust applications, which can compensate for short communication outages. By means of numerical simulations with Rayleigh fading as the cause of failure, we evaluate the performance in comparison with state-of-the-art approaches such as single-connectivity (SC), multi-connectivity, and channel hopping (CH). We demonstrate the potential of dynamic connectivity approaches (in particular RD and CH), which can improve the application outage probability by several orders of magnitude, while utilizing significantly fewer resources than static diversity schemes.

II. SYSTEM MODEL

We assume a set of N channels which are separated in frequency at least by the coherence bandwidth resulting in independent small-scale fading. We consider a single user connected simultaneously to $L \leq N$ channels. Without loss of generality, path loss and shadowing are not considered in this letter, because compensation by transmit power control or automatic gain control is assumed, as in [7]. Furthermore, the time scale of shadowing and path loss is large and, thus, not relevant for the analysis in the context of this work.

A 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 [8]. Thus, we distinguish between two states by introducing the following notation, which originates from dependability theory:

$$\text{A channel is} \begin{cases} \text{"down"}, & \text{if } p(t) < p_{\min} \\ \text{"up"}, & \text{if } p(t) \geq p_{\min} \end{cases} . \tag{1}$$

We consider a Rayleigh-faded channel following Clarke's model, whose time correlation properties are characterized by the temporal auto-correlation function

$$\theta(\Delta t) = J_0(2\pi f_{\mathrm{D}} \Delta t)\,. \tag{2}$$

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$J_0(.)$ denotes the zero-order Bessel function of the first kind and the maximum Doppler frequency is given by

$$f_{\mathrm{D}} = vf/c \tag{3}$$

with the carrier frequency of the signal f and the speed of light c. The relative velocity between transmitter, receiver, and scatterers is denoted as v. The coherence time T_{coh} is the time interval for which the correlation decreases from its maximum 1 to 0.5,

$$|\theta(T_{\mathrm{coh}})| = 0.5|\theta(0)|. \tag{4}$$

Since the time correlation function can be calculated by the inverse Fourier transform of the Doppler power spectrum, there are reciprocal relations between the coherence time and the Doppler spread. In order to estimate the coherence time, the maximum Doppler frequency f_{D} is often used according to [9]

$$T_{\mathrm{coh}} \approx \frac{9}{16\pi f_{\mathrm{D}}}. \tag{5}$$

It should be noted that the contributions of this work can be directly adopted to other channel models, which also incorporate temporal auto-correlation, e.g., Rician fading: In addition to the maximum Doppler frequency f_{D}, the temporal auto-correlation function of a Rician-faded signal

$$\theta_{\mathrm{Ric}}(\Delta t) = \frac{K \exp\left(j2\pi f_{\mathrm{D}} \cos\phi \Delta t\right) + J_0(2\pi f_{\mathrm{D}} \Delta t)}{K+1} \tag{6}$$

also depends on the K factor and the angle of arrival ϕ of the line-of-sight component [10].

III. PERFORMANCE METRICS

In this section, we introduce and compare performance metrics to evaluate robust wireless systems. The definitions are applied to Rayleigh-fading channels.

A. Outage Probability

An outage occurs when the received power level falls below a threshold $p_{\min}$. We denote the outage probability of the wireless communications system as P_{o}. The outage probability of one Rayleigh-faded channel is

$$P_{\mathrm{o},1} = \Pr[p < p_{\min}] = 1 - \exp\left(-\frac{1}{F}\right), \tag{7}$$

where $F = p_{\mathrm{avg}}/p_{\min}$ represents the fading margin with the average received power p_{avg}. Since we assume that all packets are lost during an outage, the outage probability corresponds to the packet loss rate.

B. Downtime and Uptime

The downtime τ^{d} is defined as the time interval from a transition of the instantaneous receive power level $p(t)$ to the down state $p(t) < p_{\min}$ until the first transition back to the up state $p(t) \geq p_{\min}$. The term downtime is common in classical dependability theory and corresponds to the fade duration in the context of this work.

Level crossing analysis yields the mean downtime for a Rayleigh-fading channel with Clarke's model, according to [5]

$$\bar{\tau}^{\mathrm{d}} = \frac{\sqrt{F}\left(\exp(1/F) - 1\right)}{f_{\mathrm{D}}\sqrt{2\pi}}, \tag{8}$$

which depends on the maximum Doppler shift f_{D} and, thus, on the mobility properties.

Analogously, the uptime τ^{u} specifies the duration from a transition to an up state until the first transition back to a down state. For the considered system model, the mean uptime is given by [5]

$$\bar{\tau}^{\mathrm{u}} = \frac{1}{f_{\mathrm{D}}\sqrt{2\pi}}. \tag{9}$$

Consequently, the introduced performance metrics are linked according to the basic relation [7]

$$P_{\mathrm{o}} = \frac{\bar{\tau}^{\mathrm{d}}}{\bar{\tau}^{\mathrm{d}} + \bar{\tau}^{\mathrm{u}}}. \tag{10}$$

In order to further characterize the performance of the system, we take the downtime and uptime distributions into account. Unfortunately, general closed-form solutions of the downtime and uptime distributions for Rayleigh-fading are not available. Thus, we will evaluate them by means of simulations.

C. Application Outage Probability

Some applications can bridge short communication outages with appropriate design, e.g., fault-tolerant controllers. Thus, an application outage event occurs only when the communications system exhibits a down state which lasts for more than a tolerable threshold. Hence, we define the *application outage probability* $P_{\mathrm{o}}^{\mathrm{A}}(\tau_{\max}^{\mathrm{d}})$ as the probability of experiencing fades which are longer than the maximum tolerated downtime $\tau_{\max}^{\mathrm{d}}$, i.e.,

$$P_{\mathrm{o}}^{\mathrm{A}}(\tau_{\max}^{\mathrm{d}}) = \Pr\left[p < p_{\min} \wedge \tau^{\mathrm{d}} > \tau_{\max}^{\mathrm{d}}\right]. \tag{11}$$

For a sufficiently long observation duration T, the application outage probability can be expressed by the fraction of time the system experiences outages that are longer than the threshold $\tau_{\max}^{\mathrm{d}}$, i.e.,

$$P_{\mathrm{o}}^{\mathrm{A}} = \frac{\sum_{\tau^{\mathrm{d}} \in \mathcal{C}(T)} \tau^{\mathrm{d}}}{T}, \tag{12}$$

where the set of downtimes that cause application outages is denoted by

$$\mathcal{C}(T) = \left\{\tau^{\mathrm{d}} \,|\, \tau^{\mathrm{d}} \in \mathcal{F}(T),\, \tau^{\mathrm{d}} > \tau_{\max}^{\mathrm{d}}\right\} \tag{13}$$

and the set $\mathcal{F}(T)$ contains every individual downtime τ^{d} during the time interval $[0, T]$. The metric *application outage probability* translates to the concept of minimum duration outage, published in [6], where the focus is on shadow fading. However, in this letter we propose a more precise mathematical definition. Furthermore, by utilizing the term application outage probability, we emphasize the application's ability to tolerate short outage times. It should be noted that outage probability is a special case of the application outage probability, where the maximum tolerated downtime is zero, i.e.,

$$P_{\mathrm{o}} = P_{\mathrm{o}}^{\mathrm{A}}(0). \tag{14}$$

IV. CONNECTIVITY APPROACHES

Diversity is considered to be the key technique to combat small-scale fading. By using space or frequency diversity, the information is simultaneously transmitted on independent fading channels. At the receiver side, a diversity scheme can be used to combine multiple received signals into a single improved signal. However, traditional static diversity schemes utilize many resources, even if the instantaneous channel quality is sufficient, in order to be prepared for degradation on several channels. In addition, static diversity schemes are not designed to react to instantaneous failures, e.g., by providing more resources when conditions are bad. Thus, we introduce a novel dynamic connectivity approach, which we refer to as *RD*. For comparison, CH and a multi-connectivity scheme are studied as well. As a baseline, we consider wireless communication over $L = 1$ fixed channel, denoted as SC [11].

A. Reaction Diversity

Motivated by the time-correlation properties of faded signals and the fact that robust applications tolerate short outage times, we propose the dynamic, event-driven connectivity approach RD: A user is connected to $L = 1$ channel. In case of failure, the channel is vacated and communication continues on a different channel. The order of the selected channels is assumed to be pseudo-random and predefined, taking into account that the spectral spacing of successive channels should be large to avoid correlation in frequency. For instance, a wireless closed-loop control application, which is envisioned in the context of URLLC, can then directly send the newest information, instead of re-transmitting the lost and possibly outdated packet. The channel switching procedure is assumed to take place within a reaction time t_{R}. Especially for large coherence times T_{coh} due to low mobility, the effective downtime experienced by the wireless communication system is expected to be reduced by reacting to outages instead of remaining in the faded channel. This procedure therefore also decreases the outage probability P_{o} as well as the application outage probability $P_{\mathrm{o}}^{\mathrm{A}}$ compared to SC. At the same time, RD does not utilize more resources than SC. Of course, RD needs a feedback channel, which also requires some resources (for a binary information) and can have errors. However, this is out of the scope of this paper.

B. Channel Hopping

CH is a predefined pseudo-random switching of channels and it, thus, can also be classified as a dynamic connectivity approach [12]. However, it is not adaptive because channels are continuously changed regardless of their states. We assume the constant sojourn time t_{S} in each channel. Due to the rapid switching through all N channels, the effective coherence time is reduced to the channel sojourn time t_{S}. Hence, the effective downtime is also shorter when compared with SC. For sufficiently high numbers of channels N, the wireless system experiences fades which are temporally uncorrelated. This is beneficial for robust applications, e.g., control systems which are able to compensate for short outage times. However, on average the resulting outage probability remains unchanged compared to SC with $P_{\mathrm{o},1}$ in (7) because CH continuously enters and leaves channels regardless of their current states.

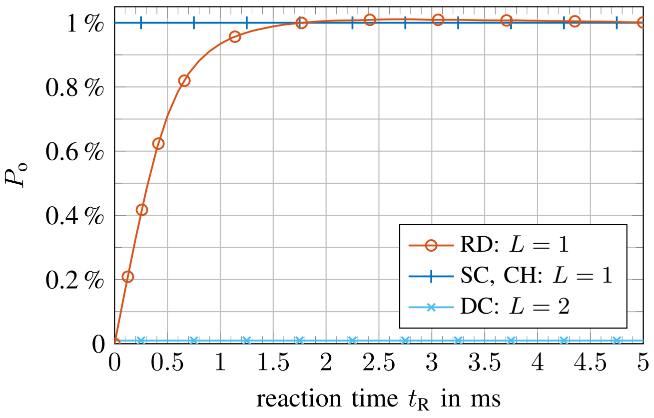


Fig. 1. Outage probability of different connectivity approaches for $f_{\mathrm{D}} = 66.7\,\mathrm{Hz}$, $F = 20\,\mathrm{dB}$.

C. Multi-Connectivity

When performing multi-connectivity, a user is connected to $L \leq N$ channels and the data is sent redundantly over each channel. In the context of this letter, we focus on the low-complexity scheme selection combining, where the best channel is selected for communication. Thus, it will be sufficient if at least one channel is up, see e.g, [13]. Assuming that all channels have identical properties, selection combining achieves a significantly improved outage probability

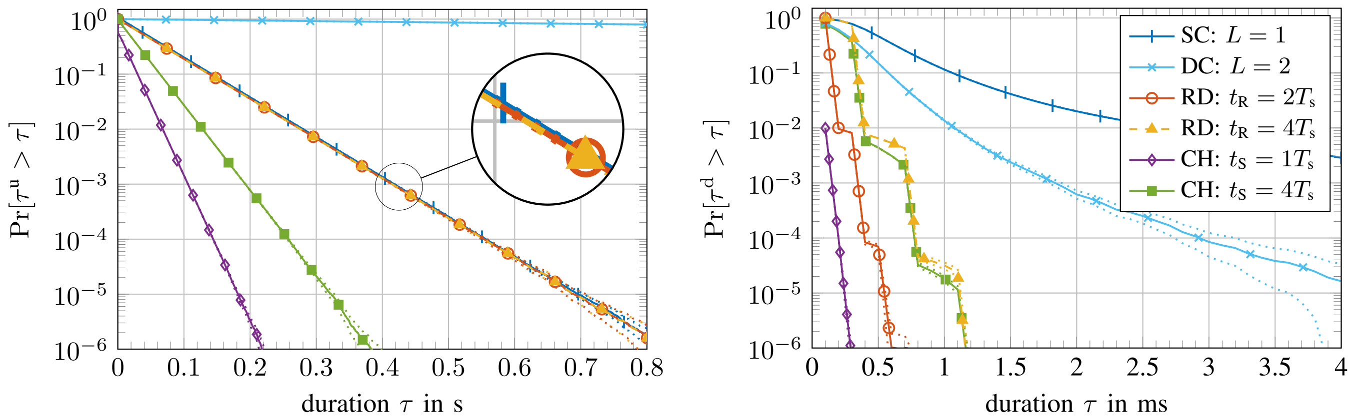
$$P_{\mathrm{o},L} = P_{\mathrm{o},1}^{L} = \left(1 - \exp\left(-\frac{1}{F}\right)\right)^{L} \tag{15}$$

compared to a non-diversity system with $L = 1$ channel, equivalent to SC. However, multi-connectivity utilizes many resources, which might not be feasible for scenarios with a high number of users. In the following, we refer to the special case of multi-connectivity with $L = 2$ channels as dual-connectivity (DC).

V. NUMERICAL EVALUATION

In this section, we compare the connectivity approaches RD, CH, DC, and SC based on numerical simulations. The introduced performance metrics are evaluated with respect to an exemplary medium-mobility scenario comprising velocity $v = 10\,\mathrm{m/s}$ and carrier frequency $f = 2\,\mathrm{GHz}$, yielding $f_{\mathrm{D}} = 66.7\,\mathrm{Hz}$. In addition, we assume a fading margin of $F = 20\,\mathrm{dB}$. All results are obtained from simulated Rayleigh fading sequences with a duration of 30 days at a sampling period $T_{\mathrm{S}} = 100\,\mu\mathrm{s}$, which is also the transmission time interval (TTI) duration.

According to (7), the outage probability of $P_{\mathrm{o},1} = 1\,\%$ is achieved by SC as well as CH. DC decreases the outage



(a) Uptime CCDF. Both RD curves coincide.

(b) Downtime CCDF.

Fig. 2. Uptime and downtime CCDFs of different connectivity approaches for $f_{D} = 66.7\,\mathrm{Hz}$, $F = 20\,\mathrm{dB}$. At each time instant CH and RD utilize $L = 1$ out of $N = 4$ channels. The dotted lines indicate the 99 % confidence bounds. The legend of (b) also applies to (a).

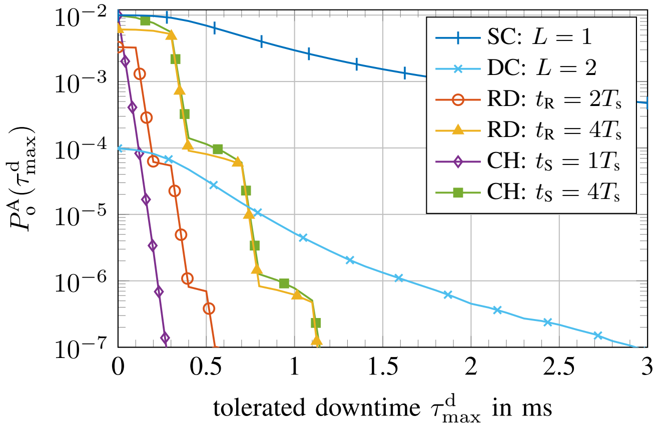


Fig. 3. Application outage probability of different connectivity approaches for $f_{D} = 66.7\,\mathrm{Hz}$, $F = 20\,\mathrm{dB}$. At each time instant CH and RD utilize $L = 1$ out of $N = 4$ channels.

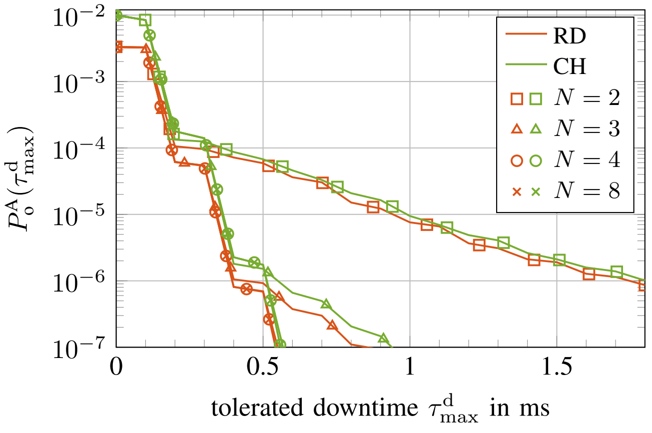


Fig. 4. Application outage probability of different connectivity approaches for $f_{D} = 66.7\,\mathrm{Hz}$, $F = 20\,\mathrm{dB}$, reaction time/channel sojourn time $t_{R} = t_{S} = 2T_{s}$, and several numbers of available channels N.

probability by two orders of magnitude per additional channel resulting from (15), i.e., $P_{o,2} = 0.01\,\%$. In Fig. 1 we compare these values with the outage probability obtained by the proposed RD approach for different reaction times t_{R}. It is clearly visible that short reaction times $t_{R} < 0.5\,\mathrm{ms}$ significantly reduce the outage probability while still only occupying $L = 1$ channel at a time. The reason is that a faded channel is swiftly abandoned, which reduces the effective duration of an outage. The outage probability of RD approaches the performance of SC and CH for larger reaction times t_{R}, because it vacates the channel to late, i.e., when it has already recovered from the outage. The slight overshoot reveals that reaction times in the range of the coherence time ($T_{\mathrm{coh}} \approx 2.7\,\mathrm{ms}$ from (5)) even lead to a slightly worse outage probability compared to SC and CH. In these cases the channel usually experiences the complete fade before switching to another channel. However, after the recovery from a fade, the probability of a new fade will be lower than on average, if we remain on the same channel. This is corroborated by taking the time-related properties of the fading process into account: The mean downtime (8) of a single channel in the considered scenario is $\bar{\tau}^{d} \approx 600\,\mu\mathrm{s}$; the mean uptime results in $\bar{\tau}^{u} \approx 59.4\,\mathrm{ms}$, confirming the fundamental relation (10).

We further delve into the time-related analysis of the fading process and the introduced connectivity approaches by presenting the empirical uptime and downtime complementary cumulative distribution functions (CCDFs) in Fig. 2. The included confidence bounds of 99 % (dotted lines) are determined by Greenwood's formula [14]. The fact that the confidence bounds are tight indicates a low uncertainty of the derived simulation results. Fig. 2(a) illustrates the probability of surpassing a certain uptime achieved by the considered connectivity approaches. DC with $L = 2$ redundant channels provides the best performance in terms of uptime. The RD curves coincide since different reaction times only affect the downtimes but have no impact on uptimes. The uptime CCDFs of RD are tightly upper-bounded by the one of SC because RD utilizes $L = 1$ channel, too. Hence, this uptime analysis immediately indicates how often channels have to be changed applying RD. The results presented can also be directly transferred to high-mobility scenarios, since the duration values scale inversely proportionally to the maximum Doppler frequency f_D and, thus, to the relative velocity v, cf. (3). CH generates significantly shorter uptimes than the proposed RD approach because CH frequently switches from an operational to a faded channel. Hence, the uptimes of CH decrease for smaller channel sojourn times. As depicted in Fig. 2(b), SC shows the highest probability of exceeding a certain downtime due to the auto-correlation properties of the Rayleigh fading process. The gain through DC with $L = 2$ redundant channels increases with larger downtime. However, both these approaches are outperformed by the dynamic connectivity concepts CH and RD for downtimes which are larger than the reaction time t_R. As expected, switching channels reduces the downtime, which leads to steps in the CCDF. The faster the channel is switched, the lower is the probability of long fades. CH slightly outperforms RD comparing the same value for reaction time and channel sojourn time, i.e., $t_\mathrm{R} = t_\mathrm{S} = 4T_\mathrm{s}$. The reason is that RD reacts to any started fade by switching the channel only after the entire reaction time has elapsed. On the other hand, CH continuously switches channels and, thus, leaves a faded channel on average twice as fast as RD. The shortest RD reaction time which is practically feasible corresponds to two packets because the event of changing channels has to be communicated via the opposite link. On the other hand, CH might theoretically be implemented with a channel sojourn time of one packet because the sequence of channels is predefined.

Studying the fade duration distributions alone is not sufficient and may even be misleading, because the time duration of fades delivers no statement on the risk of entering a fade. However, the application outage probability, presented in Fig. 3, captures this aspect. In addition, this performance metric provides insights on the impact of the tolerated downtime. In contrast to the downtime CCDF, the proposed RD scheme shows gains when compared with CH at $t_\mathrm{R} = t_\mathrm{S} = 4T_\mathrm{s}$, because CH suffers from the potential transition from an operational to a faded channel. The potential of the dynamic connectivity approaches is clearly visible, because every channel switching improves the application outage by two orders of magnitude for the chosen fading margin value: If downtimes of $\tau^\mathrm{d}_\mathrm{max} \geq 800\,\mu\mathrm{s}$ can be tolerated by the application, CH and RD with even $t_\mathrm{R} = t_\mathrm{S} = 4T_\mathrm{s}$ achieve a significantly lower application outage probability than DC over $L = 2$ channels. At the same time, the dynamic connectivity approaches utilize only half of the resources.

In Fig. 4 the effect of different numbers of available channels N on the application outage probability of RD and CH is demonstrated for $t_\mathrm{R} = t_\mathrm{S} = 2T_\mathrm{s}$. The problem of switching through channels which all are faded occurs with a probability of $P^N_{\mathrm{o},1}$. Hence, if only $N = 2$ channels can be used, immediately successive channel switches cannot significantly improve the application outage probability because of the risk that the original channel is still faded. In the range depicted, the higher numbers of channels $N = 4$ and $N = 8$ provide the same performance in terms of application outage probability. Hence, a small number of resources can be sufficient to achieve application outage probabilities which satisfy the requirements related to URLLC. This knowledge enables the design of robust multi-user systems.

VI. CONCLUSION

In this letter, we demonstrate that dynamic connectivity is a promising concept in order to combat the time-related correlation of failures in wireless communications systems with reduced resource utilization. We propose the novel approach of RD, which reacts to fades and can, thus, shorten outage events. By studying the performance metric *application outage probability*, we demonstrate the benefits of key performance indicators (KPIs) which reflect the ability of robust applications to tolerate short outage times. Consequently, requirements for other metrics, e.g., packet error rate (PER), can be relaxed while still achieving the desired performance. These investigations are basic steps to propel the co-design of wireless communications systems and robust applications, which will help mastering key challenges of URLLC applications. Potential topics of future research comprise the evaluation of the proposed dynamic connectivity approaches for other channel models, e.g., simulated Rician fading sequences, as well as coordination issues in the network.

REFERENCES

[1] M. Simsek, A. Aijaz, M. Dohler, J. Sachs, and G. P. Fettweis, “5G-enabled tactile internet,” *IEEE J. Sel. Areas Commun.*, vol. 34, no. 3, pp. 460–473, Mar. 2016.

[2] M. Bennis, M. Debbah, and H. V. Poor, “Ultrareliable and low-latency wireless communication: Tail, risk, and scale,” *Proc. IEEE*, vol. 106, no. 10, pp. 1834–1853, Oct. 2018.

[3] 3GPP TR 38.913 V14.3.0, “Study on scenarios and requirements for next generation access technologies,” *Tech. Rep.*, Jun. 2017.

[4] L. Scheuvens, T. Hößler, A. Noll-Barreto, and G. P. Fettweis, “Wireless control communications co-design via application-adaptive resource management,” in *Proc. IEEE 5GWF*, Dresden, 2019, pp. 298–303.

[5] D. Öhmann and G. P. Fettweis, “Minimum duration outage of wireless Rayleigh-fading links using selection combining,” in *Proc. IEEE WCNC*, New Orleans, Mar. 2015, pp. 681–686.

[6] N. B. Mandayam, P.-C. Chen, and J. M. Holtzman, “Minimum duration outage for cellular systems: a level crossing analysis,” in *Proc. IEEE VTC*, vol. 2, Atlanta, April 1996, pp. 879–883.

[7] T. Hößler, P. Schulz, M. Simsek, and G. P. Fettweis, “Mission availability for wireless URLLC,” in *Proc. IEEE Globecom*, Waikoloa, USA, Dec. 2019, accepted.

[8] E. N. Gilbert, “Capacity of a burst-noise channel,” *Bell Syst. Tech. J.*, vol. 39, no. 5, pp. 1253–1265, Sept. 1960.

[9] T. S. Rappaport, *Wireless communications: principles and practice*, 2nd ed. Upper Saddle River, NJ: Prentice Hall, 2002.

[10] P.-Y. Chen and H.-J. Li, “An iterative algorithm for Doppler spread estimation in LOS environments,” *IEEE Trans. Wireless Commun.*, vol. 5, no. 6, pp. 1223–1228, Jun. 2006.

[11] A. Wolf, P. Schulz, M. Dörpinghaus, J. C. S. Santos Filho, and G. P. Fettweis, “How reliable and capable is multi-connectivity?” *IEEE Trans. Commun.*, vol. 67, no. 2, pp. 1506–1520, Feb. 2019.

[12] A. A. M. Saleh, A. J. Rustako, L. J. Cimini, G. J. Owens, and R. S. Roman, “An experimental TDMA indoor radio communications system using slow frequency hopping and coding,” *IEEE Trans. Commun.*, vol. 39, no. 1, pp. 152–162, Jan. 1991.

[13] D. G. Brennan, “Linear diversity combining techniques,” *Proc. IRE*, vol. 47, no. 6, pp. 1075–1102, Jun. 1959.

[14] E. L. Kaplan and P. Meier, “Nonparametric estimation from incomplete observations,” *J. Am. Stat. Assoc.*, vol. 53, no. 282, pp. 457–481, 1958.