Efficient and Reliable Wireless Communications Through Multi-Connectivity and Rateless Coding

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***Abstract*—Achieving extremely high reliability is one of the key targets in the development of fifth generation mobile networks. To meet this ambitious aim, usually redundancy is introduced by simultaneously utilizing multiple links that are separated in frequency and/or space. However, current standards simply duplicate packets on these links, resulting in an inefficient high usage of resources that could have been used for other applications. To address this problem, rateless coding using multiple links is proposed for ultra-reliable communications, mathematically modeled, and evaluated in this paper. The benefits comprise efficient resource usage and a simplified feedback mechanism. Finally, they can be implemented in a technology-agnostic manner on application layer to easily exploit interface diversity.**

***Index Terms*—Multi-Connectivity, Reliability, Coding**

I. Introduction

The umbrella term ultra-reliable low latency communications (URLLC) denotes one of the three application domains that are envisioned to be enabled by the fifth generation (5G) of mobile communication networks. URLLC comprise mission-critical applications (e. g., control) that rely on extremely low outage probabilities and low latency. However, not all applications are sensitive to both of these key performance indicators (KPIs). There are also applications with relaxed latency constraints that only require ultra-reliable communications (URC) [1]. This perspective was already stated in [2], where mission-critical communications are classified into long and short term URC. For instance, applications from intelligent transport systems (ITS) allow a relaxed latency in the order of a few tens of milliseconds [3], [4], but need to be highly reliable. Other use cases may be found in e-health or finance.

The most promising way to achieve extremely high reliability is the introduction of redundancy, which is usually realized through time, spatial or frequency diversity. As time diversity, i. e., retransmissions, increases latency, the other two approaches are often favored. Establishing multiple links to different base stations (BSs) or using multiple antennas exploits spatial diversity, whereas the usage of different carriers is referred to as frequency diversity. Both strategies of having multiple simultaneous links are comprised in the term multi-connectivity (MC). In [5], the term interface diversity is used, which is adopted for this paper as our approach is technology-agnostic and supports being applied to multiple interfaces.

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However, in Third Generation Partnership Project (3GPP) standardization, diversity is only achieved by packet duplication on multiple links [6]. When more than one link works, which is usually the case for most of the time, there is no benefit in receiving multiple duplicates of the same packet and, thus, resources are wasted. This drawback can be eliminated by coordinated multipoint (CoMP) [7] or coding. For instance, the authors in [8] propose a K out of N erasure code for a reliable multi-path fronthaul with efficient resource usage.

In contrast, this paper proposes rateless codes (RCs) [9], which have the advantage that they do not need a priori knowledge about the loss rates to determine an appropriate code rate. The RCs are combined with an outer K out of N erasure code to improve the decoding performance. RCs are already popular in the context of video broadcasting or data storage, but have not received much interest in the area of URC so far. With RCs the simplistic K out of N assumption is no longer true.

In this regard, this article contributes as follows. RCs are studied in combination with an outer code (similar to raptor codes [10]) in terms of decoding probability and the distributions of required resources and time slots. For channels without time correlation, a fully analytical framework is provided. The proposed RC schemes are evaluated and compared to selection combining (SC) approaches as a baseline.

II. System Model

In the subsequent sections, the notation and the general scenario is described at first. Afterwards, RCs are briefly explained and the detection failure probability depending on the number of successfully received packets is derived. Subsequently, the studied MC schemes are described and, finally, the probability distributions of the required radio resources and time slots of the different schemes are derived.

A. Notation and Definitions

The complement of a given probability p is denoted as $\bar{p} := 1 - p$. A function $f_X(x)$ describes the probability mass function (PMF) of a discrete random variable X. Furthermore, the operators $\mathrm{rank}, \dim$, and span provide the rank of a matrix, the dimension of a vector space, and the vector space that is spanned by the columns of a matrix, respectively. Finally, $\lceil\cdot\rceil$ denotes the ceiling operator.

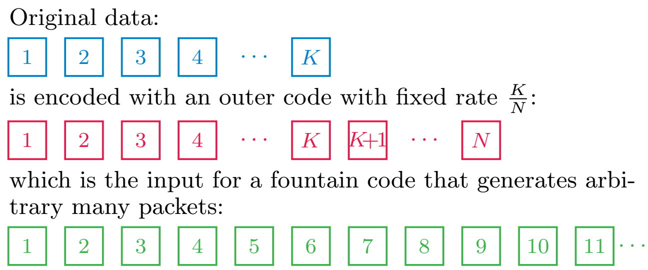


Fig. 1: Illustration of the coding scheme.

B. Scenario

In this paper, a device is connected via L links to a server and has to transmit a payload of K packets. The links are assumed to experience independent Rayleigh fading, which can be achieved for instance through spatially distributed antennas or carriers that are separated by more than the coherence bandwidth. However, the framework could be easily extended to Rician fading as well. The multi-connectivity approach pursued here is technology-agnostic, as the combining can be performed at the application layer. It is assumed that packet errors are handled by lower layers if possible, such that packets are either correctly received or completely lost. In other words, the links are assumed to be binary erasure channels (BECs).

C. Rateless Coding with Outer Coding

In the following, the concept of RC combined with an outer coding is briefly recapped. For more details, the reader is referred to [9]. RCs, which are also known as fountain codes, have no fixed code rate. In principle, infinitely many encoded packets can be generated and transmitted. A receiver only needs to collect a sufficient number of encoded packets to be able to decode the original data. An advantage of fountain codes is constituted by the fact that if some packets are lost, no feedback about which particular packets are lost is necessary, since any additional packets may lead to successful decoding. Furthermore, no a priori knowledge about the BEC is required for choosing an appropriate code rate in advance.

The required number of packets for successful decoding is usually random for rateless codes and depends on the particular packets that were received successfully. For instance, the popular Luby transform (LT) codes [11] can be tuned such that an overhead of around $5\,\%$ of the original K packets is necessary for successful decoding [9].

As illustrated in Fig. 1, this performance can be improved by introducing an additional outer code with a fixed rate. The outer code adds $N-K$ redundant packets to the original packets, such that there N encoded packets in total, and should have the property that any K out of these N encoded packets are sufficient for successful decoding. For instance, Reed-Solomon codes [12] exhibit this property.

A popular example of this two-stage coding strategy is provided by Raptor codes [10]. Raptor codes combine a low-density parity-check (LDPC) code and an LT code as the outer and inner code, respectively. However, Raptor codes are designed for large amounts of data and, therefore, focus on fast coding and decoding.

In this paper, only a small number of packets K is assumed allowing for more complex coding. Thus, a K out of N erasure code is combined with a random linear fountain code for the outer and inner coding, respectively, because the outer code guarantees that any K out of N packets of the outer code are sufficient and the random fountain code exhibits better decoding failure probabilities than LT codes, as explained in the subsequent section. This combined code will be denoted as a (K, N) RC code in the remainder of this work. By setting $N = K$, the special case of no outer code is covered as well.

Linear fountain codes are defined by a binary $K \times \infty$ generator matrix $\boldsymbol{G}$. In reality, only a finite number of columns is created, depending on how many encoded packets are required. For random linear fountain codes each element of $\boldsymbol{G}$ is chosen randomly from the set $\{0, 1\}$, excluding columns that contain zeros only. Each column of $\boldsymbol{G}$ defines an encoded packet by indicating which of the original packets are combined via a bitwise xor operation to an encoded packet.

Let $\tilde{M}$ be the number of received packets (out of M sent packets) at the device and $\tilde{\boldsymbol{G}}^{(\tilde{M})}$ be the $K \times \tilde{M}$ matrix consisting of the respective columns of $\boldsymbol{G}$. Then decoding is possible, if $\tilde{\boldsymbol{G}}^{(\tilde{M})}$ has rank K (modulo 2) and can be performed by Gaussian elimination (modulo 2).

Here, it should be noted that by using the same pseudo random numbers generator at sender and receiver, the information about which packets are contained in a received encoded packet can be reduced to a packet index. Thus, the necessary overhead is small compared to the possible payload.

D. Decoding Failure Probability

The following derivation is inspired by [10, Appendix A] and adjusted for the problem at hand. For more details the reader is referred to [10].

When a K out of N erasure code is prepended as an outer code, the matrices $\boldsymbol{G}$ and $\tilde{\boldsymbol{G}}^{(\tilde{M})}$ have the dimensions $N \times \infty$ and $N \times \tilde{M}$, respectively, but still $\operatorname{rank} \tilde{\boldsymbol{G}}^{(\tilde{M})} = K$ is sufficient for decoding, since then K packets of the outer code can be decoded, which is sufficient to decode the original data. Let $D(\tilde{M})$ define the event that $\tilde{M}$ randomly chosen packets can successfully be decoded.

Let $r := \operatorname{rank} \tilde{\boldsymbol{G}}^{(\tilde{M})} = \dim(\operatorname{span} \tilde{\boldsymbol{G}}^{(\tilde{M})})$. If now a random column $\boldsymbol{g}^{(\tilde{M})} \in \{0, 1\}^N$ is appended to $\tilde{\boldsymbol{G}}^{(\tilde{M})}$, the probability that the new column $\boldsymbol{g}^{(\tilde{M})}$ does not increase the rank is the number of elements of the subspace spanned by the columns of $\tilde{\boldsymbol{G}}^{(\tilde{M})}$ without zero divided by the number of elements of the entire space without zero, which leads to

$$\mathbb{P}\left[\operatorname{rank}\left[\tilde{\boldsymbol{G}}^{(\tilde{M})} \mid \boldsymbol{g}^{(\tilde{M})}\right] = r\right] = \frac{2^r - 1}{2^N - 1} \quad =: \bar{q}_r^{(\tilde{M})}, \quad (1)$$

$$\mathbb{P}\left[\operatorname{rank}\left[\tilde{\boldsymbol{G}}^{(\tilde{M})} \mid \boldsymbol{g}^{(\tilde{M})}\right] = r+1\right] = 1 - \bar{q}_r^{(\tilde{M})} = q_r^{(\tilde{M})}. \quad (2)$$

With this, the PMFs $\boldsymbol{r}_r^{(\tilde{M})}$ that $\tilde{\boldsymbol{G}}^{(\tilde{M})}$ has rank r can be iteratively determined by starting with $\tilde{\boldsymbol{G}}^{(1)}$ and successively adding random columns $\boldsymbol{g}^{(\tilde{M})}$ leading to the probabilities

$$\boldsymbol{r}^{(1)} = \begin{bmatrix} 1 & 0 & \dots & 0 \end{bmatrix}, \tag{3}$$

$$\boldsymbol{r}_r^{(\tilde{M}+1)} = \begin{cases} \bar{q}_r^{(\tilde{M})} \boldsymbol{r}_r^{(\tilde{M})}, & r = 0 \\ \bar{q}_r^{(\tilde{M})} \boldsymbol{r}_r^{(\tilde{M})} + q_{r-1}^{(\tilde{M})} \boldsymbol{r}_{r-1}^{(\tilde{M})}, & r > 0 \end{cases}. \tag{4}$$

In particular, the probability of the special case that $\tilde{M} = K$ packets are already sufficient can be derived as the product

$$\boldsymbol{r}_K^{(K)} = \prod_{r=1}^{K} q_r^{(r)} = \prod_{r=1}^{K} \left(1 - \frac{2^r - 1}{2^N - 1}\right). \tag{5}$$

Finally, the probability of successful decoding of a (K, N) code when $\tilde{M}$ packets are received is the probability that the rank of $\tilde{\boldsymbol{G}}^{(\tilde{M})}$ is at least K and can therefore be derived from the rank PMF as follows

$$p_{\mathrm{dec}\,K,N}(\tilde{M}) = \mathbb{P}\left[D(\tilde{M})\right] = \sum_{m=K}^{\tilde{M}} \boldsymbol{r}_m^{(\tilde{M})}. \tag{6}$$

With this derivation, the worse decoding performance of LT codes compared to random linear codes in terms of decoding failure probability can be explained. LT codes are optimized for decoding efficiency by modifying the probability distribution of the columns in $\boldsymbol{G}$ in a way that they are more likely to have only a few non-zero entries such that $\boldsymbol{G}$ is sparse. However, making some vectors more likely than others reduces the probability of picking a random vector that increases the rank of $\tilde{\boldsymbol{G}}^{(\tilde{M})}$. This behavior is illustrated in Fig. 2a–b. The histograms show how many received packets were necessary to decode the original data in $N_{\mathrm{runs}} = 10^5$ trials for an LT code and a random fountain code. Both codes were tested with and without an outer code, respectively. The figure clearly shows the decoding advantages of the random code over the LT code as well as the benefits of the introduction of an outer code. Furthermore, the analytical PMF $\boldsymbol{r}_K^{(\tilde{M})}$ that $\tilde{M}$ packets are required has been added to verify the derivation. Fig. 2c shows the decoding performances for different configurations of the (K, N) RC code for $K = 10$. It can be seen that the code can be tuned such that $\tilde{M} = 10$ received packets are sufficient with very high probability, i. e., there is no overhead due to the coding in most of the cases. This only comes with a more complex outer code for a larger N, which is acceptable for small K.

E. Multi-Connectivity Schemes

In this section, the studied transmission schemes for MC are explained. The different strategies are visualized in Tab. I. For illustrative reasons, high PLRs of $\bar{p}_{1\mathrm{tx},1} = 0.3$ and $\bar{p}_{1\mathrm{tx},2} = 0.5$ were chosen. Lost packets are written in bold red font. All schemes run until they succeed, including the retransmissions indicated by $'$ and $''$.

1) Selection Combining: The scheme SC is taken as the baseline to benchmark our approach. Here, the original packets are duplicated onto each of the L links. A packet is successfully received, if at least one of the copies has been successfully transmitted. Therefore, the scheme is easy to be implemented and exhibits no constraints on synchronization. SC has already been standardized by the 3GPP as packet duplication or dual connectivity (DC) [6]. With $p_{1\mathrm{tx},l}$ being the probability that an individual packet is transmitted successfully via the l-th link ($l \in \{1, ..., L\}$), the success probability of the SC scheme for an individual packet is the probability that not all of the links fail, which are assumed to be independent

TABLE I
ILLUSTRATION OF THE MC SCHEMES.

Time slot	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SC ($L = 1$)														
Link 1	1	**2**	3	4	**5**	**6**	7	8	9	10	2’	**5’**	6’	5”
SC ($L = 2$)														
Link 1	1	**2**	3	4	**5**	**6**	7	8	9	10	6’	**–**	–	–
Link 2	**1**	2	**3**	**4**	5	**6**	7	8	**9**	10	6’	**–**	**–**	–
RC ($L = 2$)														
Link 1	1	**3**	5	7	**9**	**11**	13	15	17	–	–	**–**	–	–
Link 2	**2**	4	**6**	**8**	10	**12**	14	16	**18**	–	**–**	**–**	–	–

$$p_{1\mathrm{tx}} = 1 - \prod_{l=1}^{L} \bar{p}_{1\mathrm{tx},l}. \tag{7}$$

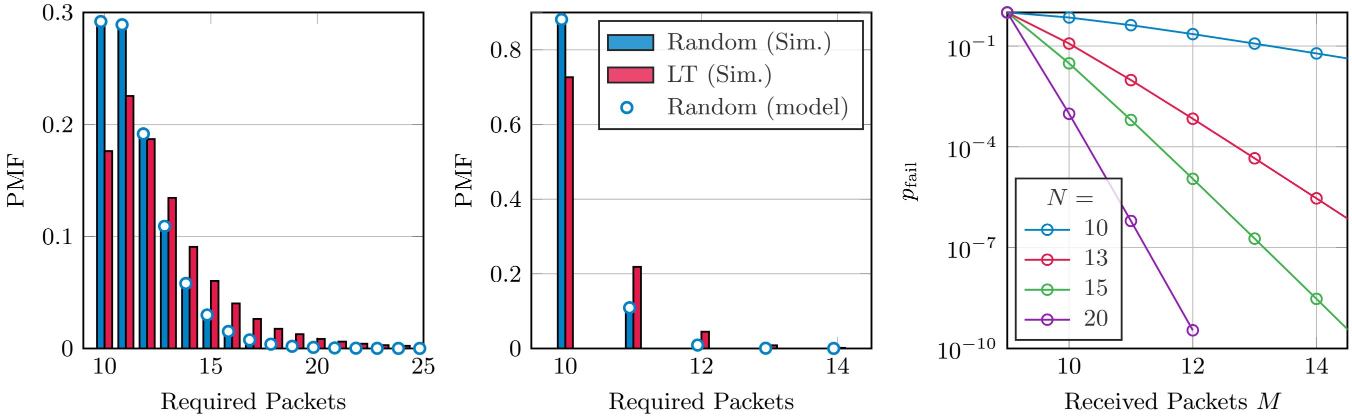
Packet duplication greatly improves reliability in terms of the packet loss rate (PLR), since outage rates are multiplied (cf. Eq. (7)). However, it also requires a lot of resources and there is no benefit when more than one link succeeds. In addition, if a packet gets lost, a feedback indicating which one is lost has to be send to allow for retransmission, which may introduce additional overhead and latency.

2) Rateless Coding (RC): In this paper, it is proposed that, rather than simply duplicating the packets on all of the available channels, the explained (K, N) RC code is utilized to generate distinct packets that are distributed over all available links. The transmission succeeds as soon as there is a sufficient number of packets available at the receiver. According to Fig. 2c, already K (or only a few more) successfully transmitted packets are sufficient up to a very high probability. The transmitter can send new packets as long as the receiver does not acknowledge a sufficient number of packages. Due to the nature of RCs, no specific knowledge is necessary about which particular packages have been lost. As each packet contributes new information with high probability, there is no wastage when more than one link succeed at the same time. In this scheme, each packet is transmitted successfully according to the probability $p_{1\mathrm{tx},l}$ of the used link l.

F. Distribution of Required Radio Resources and Time Slots

The MC schemes are compared with respect to the required radio resources R and the occupied time slots T, which are related to spectral efficiency and delay, respectively. The focus is in particular on the distribution, i. e., the PMF, of these KPIs, as this provides more insights than mean values only.

1) No Correlation in Time: At first, the special case that there is no correlation between transmissions in consecutive time slots is considered. This assumption holds when the time interval between successive packet transmissions is longer than the coherence time of the channel. Accordingly, the



(a) $K = 10, N = 10$

(b) $K = 10, N = 13$

(c) Decoding Failure Probability, $K = 10$

Fig. 2: Decoding performance. (a), (b) Comparison of the PMFs of the number of required packets for successful decoding for LT and random codes, with (a) and without (b) an outer code, respectively. (c) Analytical decoding failure probabilities for a (K, N) code for different redundancy levels.

assumption is realistic depending on the scenario at hand and in particular on the velocity of the device, the carrier frequency, and the transmission interval.

a) SC: A transmission with the SC scheme is successful after K packets are correctly received, if lost packets are retransmitted accordingly. This essentially renders Bernoulli trials in the case of no time correlation. Accordingly, $M = K$ transmissions are only sufficient, if all transmissions succeed corresponding to a probability $p_{1\text{tx}}^K$. For a successful communication after exactly $M > K$ sent packets, any $M - K$ transmissions among the first $M - 1$ transmissions have failed, which leads to the following probabilities of being successful after sending exactly M packets

$$p_{\text{rx}}(K, M) = \begin{cases} 0, & M < K \\ p_{1\text{tx}}^K, & M = K \\ \binom{M-1}{M-K} \bar{p}_{1\text{tx}}{}^{M-K} p_{1\text{tx}}^K, & M > K \end{cases}. \quad (8)$$

Since each transmission occupies one time slot in SC, Eq. (8) provides the PMF of the number of required time slots T. In each time slot, L links are utilized and, thus, the number of required radio resources is expressed as $R = L \cdot T$, leading to a scaling of the PMF by the factor L.

b) (K, N) Rateless Coding: At first, the special case that all links are equally strong and therefore exhibit the same success probability, i. e., $p_{1\text{tx},l} = p_{1\text{tx}}$ for $l \in \{1, \dots, L\}$, is considered. If all links have equal probabilities, Eq. (8) holds again, but for distinct packets on single links.

In the general case, i. e., for arbitrary $p_{1\text{tx},l}$ for $l \in \{1, \dots, L\}$, one is confronted with generalized Bernoulli trials. As the Mth packet is transmitted on the $(1 + M \bmod L)$th link, the Mth Bernoulli trial has the success probability $q_M = p_{1\text{tx},1+M \bmod L}$. The PMF values $\boldsymbol{p}_m^{(M)}$ of achieving exactly m successful transmissions out of M transmissions can be obtained iteratively with a similar procedure as conducted in Section II-D with the probabilities q_M by setting $\boldsymbol{p}^{(1)} = \begin{bmatrix} 1 & 0 & \dots & 0 \end{bmatrix}$ and

$$\boldsymbol{p}_m^{(M+1)} = \begin{cases} \bar{q}_M \boldsymbol{p}_m^{(M)}, & m = 0 \\ \bar{q}_M \boldsymbol{p}_m^{(M)} + q_M \boldsymbol{p}_{m-1}^{(M)}, & m > 0 \end{cases}. \quad (9)$$

From this PMFs the probability of successfully receiving exactly $\tilde{M}$ out of M packets can be extracted as

$$p_{\text{rx}}(\tilde{M}, M) = \boldsymbol{p}_{\tilde{M}}^{(M)}. \quad (10)$$

For the number of required resources, the decoding failure probability has to be incorporated as well. Accordingly, the (K, N) RC coding is successful for M sent packets, if $\tilde{M}$ packets are received and can be decoded, which results in a sum of conditioned probabilities

$$p_{\text{suc}}(M) = \sum_{m=K}^{M} \mathbb{P}\left[D(\tilde{M}) \mid \tilde{M} = m\right] \quad (11)$$

$$= \sum_{m=K}^{M} p_{\text{dec}\,K,N}(m) p_{\text{rx}}(m, M). \quad (12)$$

Since L links are used, the proposed scheme always occupies multiples of L radio resources in each time slot, the PMF of the required radio resources can be obtained by aggregating the success probabilities of the respective packet numbers accordingly

$$f_R(k) = \begin{cases} \sum_{l=0}^{L-1} p_{\text{suc}}(k - l), & k \bmod L = 0 \\ 0, & \text{otherwise} \end{cases}. \quad (13)$$

Finally, the PMF of occupied time slots T can be obtained by summing the success probabilities of packet numbers that lead to number of time slots of interest

$$f_T(t) = \sum_{l=0}^{L-1} p_{\text{suc}}\left(\left\lceil \frac{t}{L} \right\rceil - l\right). \quad (14)$$

2) Channels with Time Correlation: If there is correlation in the time domain, the aforementioned derivations are not valid anymore and the analysis is, to the best of our knowledge, hardly tractable. Consequently, the schemes are only evaluated by simulation in this case.

III. Numerical Evaluation and Validation

For the evaluation of the proposed schemes and the validation of the derived models, a scenario with three BSs mounted at $32\,\mathrm{m}$ with a transmit power of $49\,\mathrm{dBm}$, which are located at the corners of an equilateral triangle with an inter-site distance of $100\,\mathrm{m}$, is considered. A standard 3GPP path loss model from [13] is chosen to obtain the average power P_{avg} a device at a given location receives from each BS. For schemes that do not utilize all three potential links, the strongest links are chosen, based on P_{avg}.

The system operates at a carrier frequency $f_{\mathrm{c}} = 2.4\,\mathrm{GHz}$ and a device velocity $v = 10\,\mathrm{m\,s^{-1}}$ is assumed, leading to an estimated coherence time of $T_{\mathrm{coh}} \approx 2\,\mathrm{ms}$. Based on this, the links are simulated as independent Rayleigh fading channels. A packet sent at time t is considered to be successfully received, when the instantaneous receive power $P(t)$ exceeds a given threshold $P_{\mathrm{min}} = -100\,\mathrm{dBm}$. Based on this, the PLR can be obtained via

$$\bar{p}_{1\mathrm{tx},l} = 1 - \exp\left(-\frac{1}{P_{\mathrm{avg},l} - P_{\mathrm{min}}}\right). \tag{15}$$

Two scenarios are considered:

1) The device is located in the center of all BSs and, thus, receiving equally strong signals leading to the same PLR $\bar{p}_{1\mathrm{tx},l} = 0.12$ on each link ($l \in \{1, 2, 3\}$).
2) The device is located at a fixed location $17\,\mathrm{m}$ away from the center, resulting in different signal strengths and different PLRs $\bar{p}_{1\mathrm{tx},1} = 0.02$, $\bar{p}_{1\mathrm{tx},2} = 0.13$, and $\bar{p}_{1\mathrm{tx},3} = 0.54$.

For all experiments, the number of original packets and the encoded packets by the outer code are fixed to $K = 10$ and $N = 20$, respectively

It should be noted that the exemplary settings applied here for evaluation could be easily substituted with other configurations. However, the presented results mostly depend on the PLR values and the correlation in time.

The results are depicted in Fig. 3. All empirical complementary cumulative distribution function (CCDF) curves are obtained from 10^6 simulated samples.

A. No Correlation in Time

By choosing $T_{\mathrm{s}} = 10\,\mathrm{ms} > T_{\mathrm{coh}}$, the channel can be considered as uncorrelated in time. With this setting, the Figs. 3a, b, e, and f have been created. The plots contain the empirical CCDFs as well as the values obtained from the models derived in Section II-F.

First, it can be observed that model and simulation results agree well. It should be noted that the simulated curves suffer from inaccuracies particularly at the distribution tail, i. e., as the empirical curves have been obtained from 10^6 samples, they are not reliable in the order of magnitude around 10^{-6} anymore. In contrast, the models can be evaluated for extremely low outage values without significant effort.

Furthermore, the curves of the radio resources exhibit typical steps for schemes with more than one link, as only multiples of the number of links are utilized. For equally strong links (a), the CCDFs of the RC schemes behave very similarly to the SC curve for one link, with the only difference that values which are not multiples of L are infeasible. This is expected, because for equal, uncorrelated links, it does not matter whether packets are transmitted via one ore multiple links. However, in the case of unequally strong links (b), the RC schemes suffer from the fact that they utilize bad links as well. Nevertheless, the RC schemes outperform the SC schemes with more than one link as the SC schemes need at least 20 and 30 radio resources, respectively.

Clear advantages of RC can be observed by comparing the distributions of occupied time slots (c), (d). Both RC schemes outperform all SC schemes. Furthermore, SC with only one link may require many time slots, even though it might be the most efficient scheme in terms of radio resources. It should also be noted that the SC scheme needs to send a feedback for each packet that is not correctly received, which contains the information about which packet has to be retransmitted. This feedback overhead equals the number of time slots that exceed K. In contrast, one simple acknowledgement in the end is sufficient for the RC schemes.

B. Channels with Time Correlation

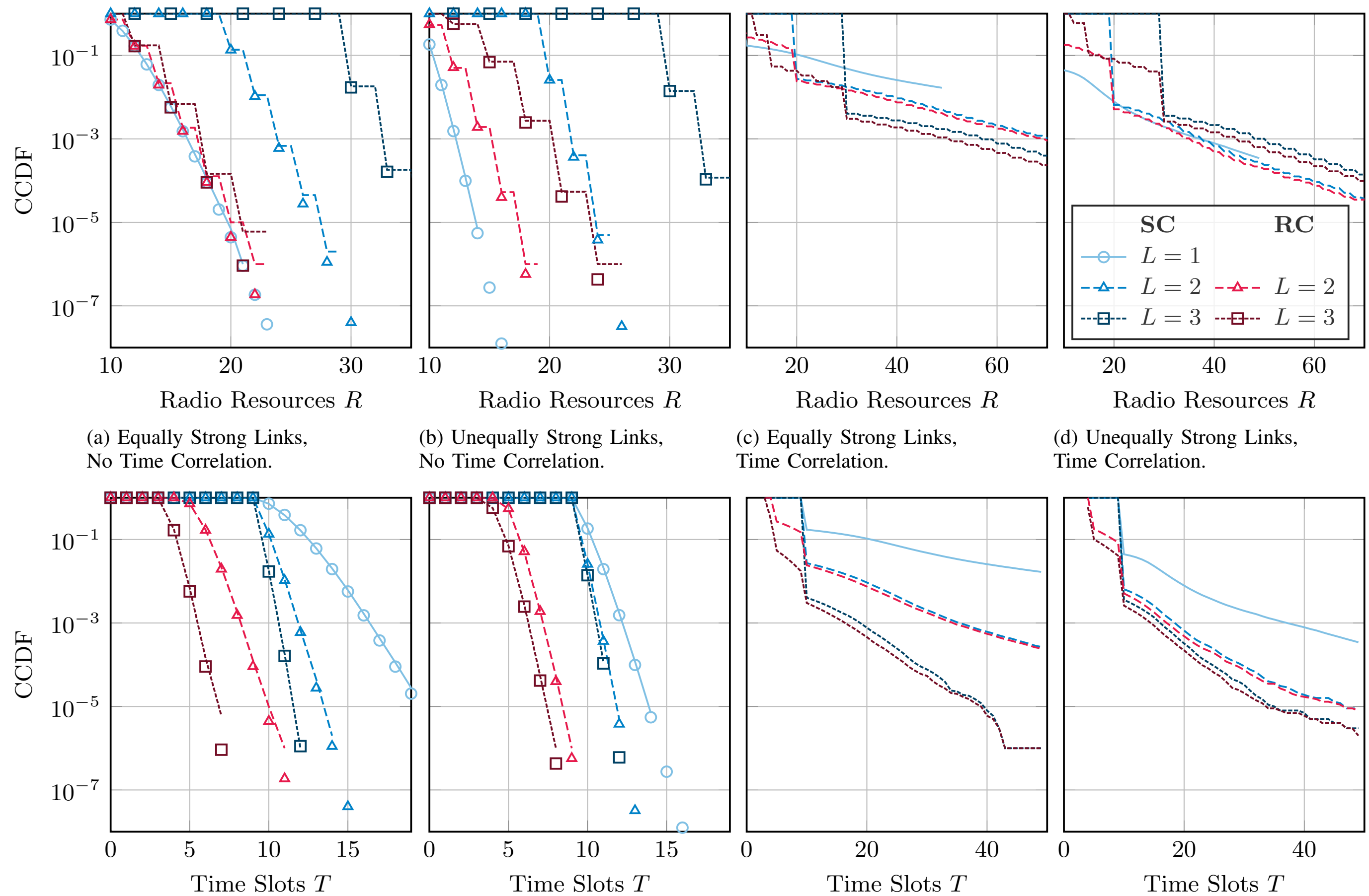
The same studies have been conducted for $T_{\mathrm{s}} = 0.1\,\mathrm{ms} < T_{\mathrm{coh}}$, which leads to highly correlated channels in time, and their results are depicted in Figs. 3c, d, g, and h. No model results are available in this case. As a general observation it can be stated that the curves exhibit a flatter tail than in the uncorrelated case, which is due to the fact that once a scheme suffers from fading, it is very likely to stay in this state for the next transmissions.

Again, SC with one link is efficient in terms of resource usage in most of the cases. However, for equally strong links (a) the worst distribution tail can be observed for this scheme, as it may get stuck in a deep fade. For unequally strong links (b) SC with one link has the advantage that only the strongest link (on average) is used.

Both RC schemes outperform their SC counter parts in terms of radio resource usage, especially in the lower part of the distribution, which accounts for the majority of realizations (more than $90\,\%$, which corresponds to the 10^{-1} value of the CCDFs). At the distribution tail, a minor advantage can still be observed. The distributions of the occupied time slots (e), (f) exhibit a similar behavior and expose clear disadvantages of the SC scheme with one link. Again, it should be noted that this scheme suffers from the control overhead that is introduced by the required feedback.

IV. Conclusion and Outlook

In this paper, a MC transmission scheme based on RC combined with an outer code, which adds computational



(a) Equally Strong Links, No Time Correlation.
(b) Unequally Strong Links, No Time Correlation.
(c) Equally Strong Links, Time Correlation.
(d) Unequally Strong Links, Time Correlation.
(e) Equally Strong Links, No Time Correlation.
(f) Unequally Strong Links, No Time Correlation.
(g) Equally Strong Links, Time Correlation.
(h) Unequally Strong Links, Time Correlation.

Fig. 3: Comparison of the transmission schemes in terms of (a)–(d) required radio resources R and (e)–(h) occupied time slots T. Results are shown for equally strong links (odd) and unequally strong links (even), respectively. Furthermore, the experiments are conducted with (right) and without time correlation (left). The legend in (d) applies to all plots. Markers indicate model results, whereas lines refer to simulations.

complexity but no overhead with high probability, was studied analytically and by simulations. Compared with state-of-the-art SC schemes, RC has clear advantages compared to the resource utilization, especially when applied on equally strong links. In a real scenario, this situation could be achieved by means of power control or rate adaptation at the physical layer. Even though the proposed RC schemes are designed to efficiently achieve reliable transmissions, they are more relevant for URC rather than for URLLC applications, since the data is spread over multiple time slots. Future studies may include multi-user scenarios as well as low-latency considerations.

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