Channel Coding Versus Cooperative ARQ: Reducing Outage Probability in Ultra-Low Latency Wireless Communications

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Abstract—**Nowadays wireless communications still lack the ability to provide high reliability and low latency, although mission-critical applications, such as found in industrial automation, rely on both requirements. The main challenge is that an improved reliability often comes at the price of an increased latency. It has been shown that cooperative schemes can effectively increase the reliability by leveraging spatial diversity. However, an important question remains how to integrate cooperative schemes when dealing with very short latency bounds and especially how much time should be reserved for potential retransmissions. In this work, we propose and evaluate a centralized communication system that uses cooperative ARQ to achieve high reliability under the constraint of a strict latency bound of 1 ms. We evaluate this system analytically, using an outage-capacity model with average channel state information, by varying the reserved time for retransmissions, where a shorter time for retransmissions allows to apply stronger channel codes in the original transmission. As a baseline, we use a system without cooperation mechanism, thus applying the given time for stronger channel codes in the direct transmission of a message. In case of cooperation, a third station may act as a relay if the original transmission failed. Our results reveal that an optimal size of the reserved retransmission time exists around 15% to 30% of the total frame time, increasing the reliability by several orders of magnitude, even for a large number of transmissions within a communication cycle.**

I. INTRODUCTION

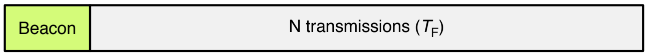
While wireless communications are well established in private homes and business environments, industrial automation systems still mainly rely on wired fieldbuses for communication due to the strong guarantees, in terms of low latency and high reliability, provided by fieldbuses. However, attention is shifting to replace the hitherto existing wired systems with wireless communications, as the flexibility in the deployment and maintenance allows for more complex and efficient production processes and subsequently leads to a reduction of costs [1]. Nevertheless, safety- and mission-critical applications, which are part of industrial automation, require ultra-low latency and ultra-high reliability for communication, which common wireless standards, such as the IEEE 802.11 standards or Bluetooth, currently do not offer. Although there are standards for wireless communication technologies that were specifically developed for industrial automation, such as WirelessHART and ISA100.11a [2], they are not able to provide strong guarantees and their performance is affected by co-existing wireless technologies, as they only apply blacklisting in order to mitigate co-channel interference.

In the context of safety- and mission-critical applications, achieving ultra-low latency and ultra-high reliability is defined as transmitting a message within a few milliseconds with a guaranteed outage probability below 10^{-9} [3]. Current wireless systems fail at providing such guarantees for several reasons:

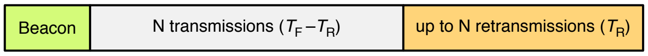
(i) Radio signal propagation is strongly affected by fading, absorption, diffraction and scattering, whose impacts are easily in the order of the target latency constraints;
(ii) Wireless transmissions are subject to co-channel interference, especially in unlicensed frequency bands; and
(iii) Access to the shared wireless medium is often not deterministic due to random back-off schemes, which impede the compliance of transmission time bounds.

In general, communication reliability can be increased by exploiting different diversity schemes in time, frequency, and space. Solely relying on time diversity is prohibitive in case of the ultra-low latency requirement imposed by the application. Then again, frequency diversity is known to improve the reliability considerably if frequency bands are statistically uncorrelated [4]. Yet, this type of diversity is not considered to improve the overall spectral efficiency and to avoid control overhead to synchronize the frequency hopping sequences among various such networks. Out of the different types of spatial diversity, where multi-antenna and cooperative schemes are the most important ones [5], multi-antenna diversity benefits from a better sensitivity against small-scale fading effects by using Space Time Block Codes (STBCs), but is still sensitive to shadowing effects. Moreover, these schemes cause higher costs and a worse form factor as multiple antennas are required on transmitters and / or receivers. On the other hand, cooperative schemes form a virtual antenna array across stations which allows to have simple devices and better protection against shadowing at the expense of dedicated retransmission time slots. Regarding the medium access, a deterministic scheme needs to be considered to allow each station in the network to send its information. Then again, a complicated question remains which diversity techniques should be incorporated into medium access schemes, given a strict transmission time bound.

In this paper, we propose a centralized Time Division Multiple Access (TDMA) system that trades time diversity against cooperative diversity to increase the reliability while guaranteeing strict latency bounds using cooperative Automatic Repeat reQuest (ARQ) [6]. There, the coding rate of the original transmissions is reduced to reserve some time of the



(a) TDMA frame when applying CODING.



(b) TDMA frame when applying COOP. ARQ.

Fig. 1. TDMA frames for the two proposed design options. In case of COOP. ARQ (b) the retransmissions are done by the local BS.

frame for potential retransmissions. The retransmissions are centrally performed at the local Base Station (BS) to save time as reacting to failed transmissions requires rescheduling of time resources and signaling overhead. The fixed duration for retransmissions is then shared by all failed transmissions and their coding is dynamically adapted to the available time. The main contribution of this paper is how much time resources to sacrifice for the original transmission to enable a substantial improvement in the retransmission phase, especially as we expect only a few messages to be retransmitted due to multi-user diversity, i. e., the probability that multiple transmissions fail in the same frame is comparably low. As a baseline, we consider an approach that is solely based on Forward Error Correction (FEC) and aims to prevent packet losses by applying strong channel codes for the transmissions within the available time. We thus analyze to which extent channel codes and cooperative ARQ should be applied in a time-sensitive approach by defining a system model based on the Shannon capacity and a flat, block-fading Rayleigh channel to derive the system outage probability for the different design options.

The remainder of the paper is structured as follows: Sec. II defines the system model for our analysis. In Sec. III, we derive the system outage probability departing from the proposed model. An analytical evaluation of the expected outage probability is presented in Sec. IV. An overview of related work is provided in Sec. V. Sec. VI concludes this paper.

II. SYSTEM MODEL

We consider a local cell with N stations and an additional local BS, where all stations are in communication range. The local BS is in charge of the centralized Medium Access Control (MAC) and thus grants the stations access to the shared medium. It applies a TDMA scheme with a fixed frame size for each communication cycle of duration T_cyc. Within a frame, each Transmitting Station (Tx) sends one after the other exactly one message of size D directly to a Receiving Station (Rx), which is also located within the local cell. The BS overhears all transmissions within the local cell and can thus tell whether a message was successfully transmitted or not. In the following, we present a medium access model including two options for the TDMA frame design. Then, the assumptions that we make regarding wireless transmissions between Tx and Rx are defined. Based on these assumptions, we calculate the outage probability for a single link to derive our system model. The resulting model ultimately leads to the calculation of the system outage probability, which we present in Sec. III.

A. Medium Access Model

We assume that a local cell operates in a wireless transmission channel exclusively. The BS grants access rights by applying TDMA. Concerning the TDMA frame structure, we consider two different options, which are both depicted in Fig. 1. Both frame options begin with a beacon message from the BS, which serves for the connected stations as a time reference indicating the beginning of a new frame. The first option serves as a baseline and is referred to as CODING. Unsuccessfully transmitted messages are not retransmitted, such that the whole frame time T_F is reserved for the N transmissions. Subsequently, a single message is transmitted in time $T_\mathrm{t} = {}^{T_\mathrm{F}}\!/_{N}$. In the second option, which we refer to as COOP. ARQ, we reserve a certain portion of T_F, denoted by T_R, in which the BS retransmits all messages that were not correctly received by their respective Rx. A single message is now transmitted in a shorter time $T_\mathrm{t} = {}^{(T_\mathrm{F}-T_\mathrm{R})}\!/_{N}$. This implies that the coding rate for the respective message must be adapted in order to fit the entire message into the designated time slot. The duration T_R is reserved solely for the BS to retransmit messages that were not successfully received. Given that $x \leq N$ original transmissions failed, these messages are retransmitted in time slots of length $T_\mathrm{ret} = {}^{T_\mathrm{F}}\!/_{x}$. Hence, T_R is *dynamically* divided into slots depending on x, which means that for a larger x the coding of the retransmitted messages must be reduced. Note that we expect x to be on average significantly smaller than N, as the probability of multiple erroneous transmissions within T_cyc is very low. The successful reception of a message at the receiver is signaled by an acknowledgement (ACK), i. e., if the BS misses an ACK, it schedules the respective message for retransmission. As ACKs only contain one bit of information, we assume a dedicated, loss-free channel for ACKs, which does not affect the outage probability.

An example for the two frame design options is depicted in Fig. 2. It includes a scenario where three messages need to be transmitted within one frame and illustrates how the respective frames are structured at the different transmission stages.

B. Wireless Channel Model

The considered network operates in a wireless channel exclusively. This channel occupies bandwidth B. Frequency variability over B is not considered, i. e., the channel is assumed to be flat. A wireless transmission within the local cell is not affected by interference, but experiences path loss, shadowing[1] and fading. Further, we assume that Rx has instantaneous Channel State Information (CSI), obtained from training information in the packet, whereas Tx only has average CSI. We use the instantaneous (γ) and average ($\overline{\gamma}$) Signal to Noise Ratio (SNR) as CSI, respectively.

In our model, we consider a block-fading Rayleigh-channel. The corresponding Probability Density Function (PDF) of the SNRs follows an exponential distribution and is given by

$$p_{\overline{\gamma}}(\gamma) = \frac{1}{\overline{\gamma}} \cdot \exp\left[-\frac{\gamma}{\overline{\gamma}}\right] \quad . \tag{1}$$

Regarding the link qualities within the cell, we differentiate between a link between two stations and between a station and the BS. While stations are assumed to have similar (simple) hardware characteristics, the BS may include more complex hardware features and additionally is expected to have a central position within the cell. To allow for computationally tractable

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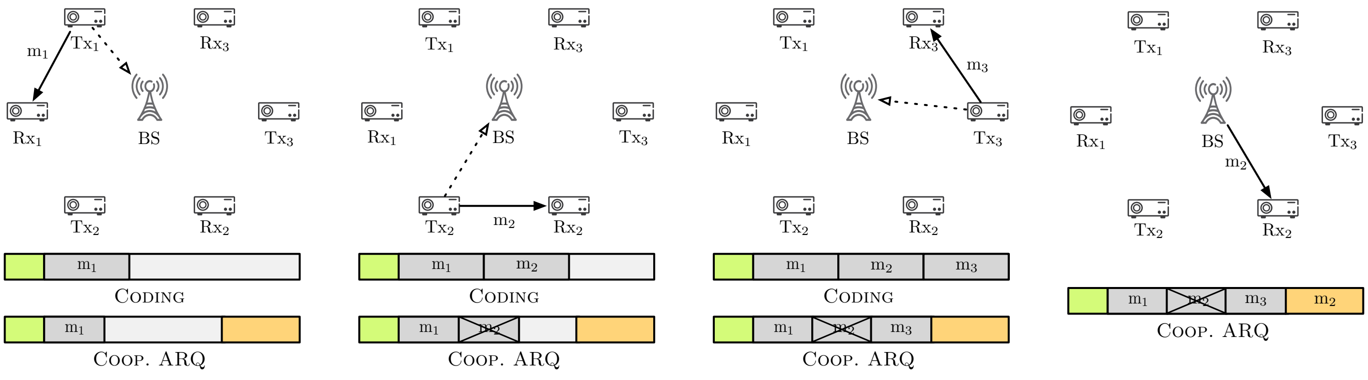
[1] Shadowing is currently not considered in the evaluation model.



(a) Transmission of m_1. (b) Transmission of m_2. (c) Transmission of m_3. (d) Retransmission of m_2.

Fig. 2. Example scenario for CODING (a)–(c) and COOP. ARQ (a)–(d). Within the respective frames, three messages m_1, m_2 and m_3 have to be transmitted. In the case of COOP. ARQ, m_2 is not correctly received by Rx_2. The BS, which overheard m_2 in (b), retransmits the message in the retransmission phase (d).

expression, we assume symmetric wireless channel conditions. We thus introduce $\overline{\gamma}_{\text{L}}$ representing the average received SNR at a link between two stations and accordingly $\overline{\gamma}_{\text{BS}}$ for the average received SNR at a link between a station and the BS.

C. Error Model

We consider the outage probability model [7, Eq. (3.3.26)] as the error model for a single transmission. It originates from the calculation of the expectation of the Shannon capacity marginalized over the fading realizations caused by a flat block-fading Rayleigh channel. It is given as

$$\begin{aligned}\mathbb{P}_{\text{out}} &= \Pr\left\{\frac{C(\gamma)}{B} \leq R\right\} \\ &= 1-\exp\left[-\overline{\gamma}^{-1}\left(2^{R}-1\right)\right]. \qquad (2)\end{aligned}$$

Eq. (2) describes how probable it is that for a random point in time, the actual capacity $C(\gamma)$ is sufficient to reliably convey a message that needs to be sent with normalized rate R (bits per unit bandwidth). This rate R is given as

$$R = \frac{D}{B\cdot\tau}, \qquad (3)$$

in which D is the message size, B is the transmission bandwidth, and τ corresponds to the available time span for transmission. This allows to define the outage probability used in the remainder of this work as

$$\mathbb{P}_{\text{out}}(\overline{\gamma},\tau) \triangleq 1-\exp\left[-\overline{\gamma}^{-1}\left(2^{\frac{D}{B}\cdot\frac{1}{\tau}}-1\right)\right]. \qquad (4)$$

III. SYSTEM OUTAGE PROBABILITY

In the following, we derive the total message error probability for a station, ϵ, for our two design options, i. e., COOP. ARQ and CODING, to compute the respective total outage probability for each transmitted message. Afterwards, the expected performance is evaluated in Sec. IV.

A. Coding

In case that the BS does not retransmit messages, each of the N stations has only one shot to transmit a message correctly, but has its full share of time to do so, i. e., T_{F}/N.

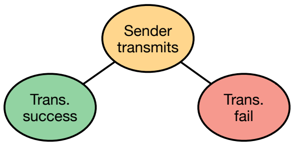


Fig. 3. Probability tree without COOP. ARQ.

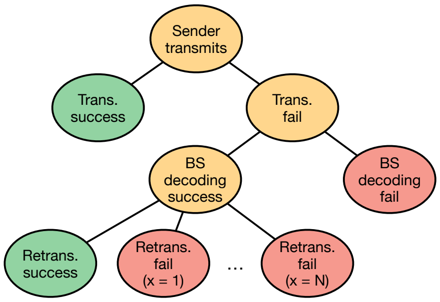


Fig. 4. Probability tree with COOP. ARQ.

Employing ARQ on such short time scales in case of time-correlated channels is not considered, since transmitting via FEC with a higher code rate is more beneficial [8].

The corresponding probability tree for a single transmission of each message is show in Fig. 3, and thus, contains exactly two leafs: One representing a successful reception of the message and the other one representing a transmission failure. The message error probability, ϵ, can then be directly derived using the outage probability (cf. Eq. (2)) as

$$\begin{aligned}\epsilon &= \mathbb{P}_{\text{out}}\left(\overline{\gamma}_{\text{L}}, \frac{T_{\text{F}}}{N}\right) \\ &= 1-\exp\left[-\overline{\gamma}_{\text{L}}^{-1}\left(2^{\frac{D}{B}\cdot\frac{N}{T_{\text{F}}}}-1\right)\right]. \qquad (5)\end{aligned}$$

B. Cooperative ARQ

When enabling COOP. ARQ, we have to adapt the probability tree of Fig. 3 by extending the case when the message does not correctly arrive at the receiver. The probability tree including COOP. ARQ is shown in Fig. 4. In case the original message did not arrive at the receiver, we have to consider whether the BS could overhear the original message or not. In the event that the original message could not be decoded by the BS, it can not be scheduled for retransmission and, thus, has to be considered lost. Otherwise, the BS will schedule the message in the retransmission phase at the end of the TDMA frame. The probability that a BS is able to schedule a message for retransmission requires an unsuccessful direct transmission and successfully overhearing the direct one (middle circle in Fig. 4), and can be described using

$$\mathbb{P}_{\text{RET}} = \mathbb{P}_{\text{out}}\left(\overline{\gamma}_{\text{L}}, \frac{T_{\text{F}} - T_{\text{R}}}{N}\right) \cdot \left(1 - \mathbb{P}_{\text{out}}\left(\overline{\gamma}_{\text{BS}}, \frac{T_{\text{F}} - T_{\text{R}}}{N}\right)\right). \quad (6)$$

A successful message transmission in the retransmission phase thereby depends on the total number of messages scheduled for retransmission since all these messages need to share the fixed time for retransmission equally. As it is unknown upfront how many messages are erroneous, the BS has to allocate a certain duration for retransmissions, T_{R}. The more messages have to be retransmitted within this duration, the less time is available for each of them. Thus, the outage probability increases with a higher number of scheduled retransmissions. This further means that we have to marginalize the resulting outage probability over the occurrence probability that $x \in \{1, \ldots, N\}$ messages have to be repeated (retransmission branch in lower right in Fig. 4). The total message error probability, ϵ, when including Coop. ARQ is then defined as

$$\begin{aligned}\epsilon = {} & \mathbb{P}_{\text{out}}\left(\overline{\gamma}_{\text{L}}, \frac{T_{\text{F}} - T_{\text{R}}}{N}\right) \cdot \mathbb{P}_{\text{out}}\left(\overline{\gamma}_{\text{BS}}, \frac{T_{\text{F}} - T_{\text{R}}}{N}\right) \\ & + \mathbb{P}_{\text{RET}} \cdot \sum_{x=1}^{N} \mathbb{P}_{\text{out}}\left(\overline{\gamma}_{\text{BS}}, \frac{T_{\text{R}}}{x}\right) \cdot P(x) \quad , \quad (7)\end{aligned}$$

where $P(x)$ denotes the probability that exactly x messages from other stations are also scheduled for retransmission and, assuming a binomial distribution, is given as

$$P(x) = \binom{N-1}{x-1} \mathbb{P}_{\text{RET}}^{x-1} \left(1 - \mathbb{P}_{\text{RET}}\right)^{N-x} \quad . \quad (8)$$

The first additional term in Eq. (7) describes the probability that the original message was not received correctly by Rx and that at the same time, the BS was not able to receive it either. The second term represents the case in which the BS overheard the message, but fails to forward it to Rx depending on how many other messages have to be retransmitted in addition.

IV. Analytical Evaluation

In this section, we analytically evaluate the total message error probability (ϵ) with regard to the question on whether applying cooperative ARQ or stronger coding when considering the same time bound for both options. Further, in case of Coop. ARQ, we also evaluate the behavior of the total message error probability for different parameterizations, and answer the question of how large to choose T_{R} before knowing how many messages have to be repeated.

For the analysis, we consider two basic scenarios: In the first scenario (A), the links between the stations are of high quality, whereas the links to and from the BS are of low quality, i. e., $\overline{\gamma}_{\text{L}} \gg \overline{\gamma}_{\text{BS}}$. In the second scenario (B), the links between the station have a mediocre quality, whereas the links to and from the BS have a better quality, i. e., $\overline{\gamma}_{\text{L}} \ll \overline{\gamma}_{\text{BS}}$.

TABLE I. Evaluation Parameters.

Symbol	Value	Description
N	5	Number of transmissions per frame
D	128 bit	Message size
$\overline{\gamma}_{\text{L}}$	25 dB (A) 15 dB (B)	Avg. SNR for links between the stations
$\overline{\gamma}_{\text{BS}}$	15 dB (A) 25 dB (B)	Avg. SNR for links from and to the BS
B	20 MHz	Transmission bandwidth
T_{F}	1 ms	Total frame time for transmissions
T_{R}	$\alpha \cdot T_{\text{F}}; 0 < \alpha < 1$	Total frame time for Coop. ARQ
α	$\{0, 0.1, 0.2, 0.5\}$	Portion of T_{F} used for Coop. ARQ

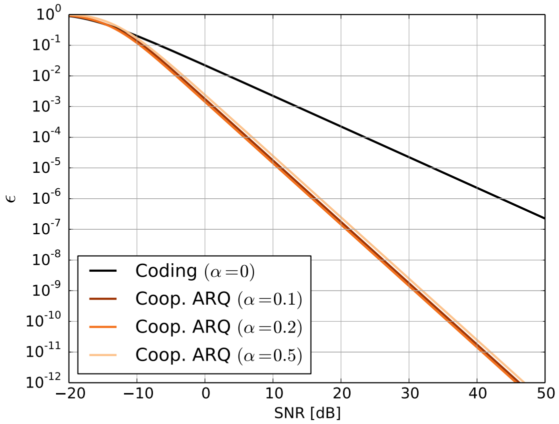


Fig. 5. ϵ depending on $\overline{\gamma}_{\text{L}}$ for different portions of α. The links between the stations and the links to the BS are homogeneous. The respective average SNR values are equal and set according to the first axis.

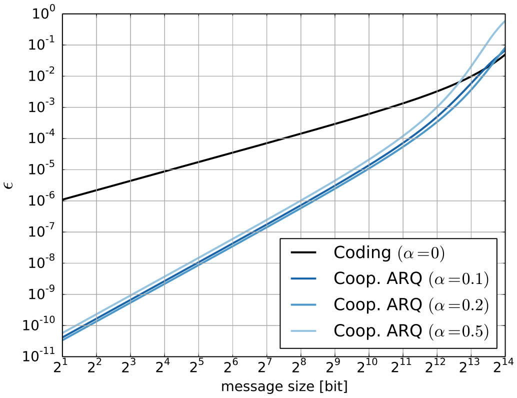
The parameters of the analysis are summarized in Table I. A high quality link in scenarios (A) and (B) is considered to have an average SNR of $\overline{\gamma} = 25\,\text{dB}$, whereas a low quality link is considered to have an average SNR of $\overline{\gamma} = 15\,\text{dB}$. Furthermore, we vary the frame time for Coop. ARQ, T_{R}, by choosing different portions $\alpha \in \{0, 0.1, 0.2, 0.5\}$ of T_{F}.

A. Homogeneous Links

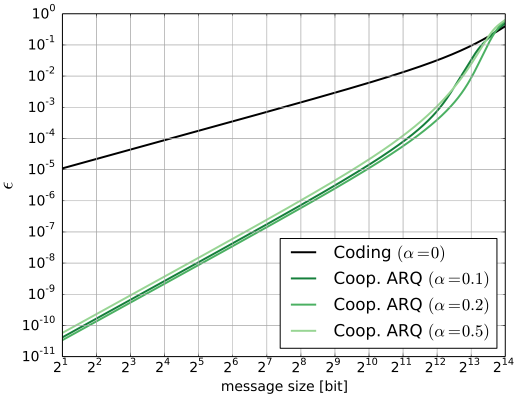
Before analyzing both scenarios, we evaluate the impact of the average SNR on Coop. ARQ and Coding assuming a fully symmetric topology in the network, i. e., $\overline{\gamma}_{\text{L}} = \overline{\gamma}_{\text{BS}}$. We thus vary the average SNR for each link between the extreme cases of -20 dB and 50 dB for $\alpha \in \{0, 0.1, 0.2, 0.5\}$. The results are shown in Fig. 5.

For both cases, i. e., with and without Coop. ARQ, the outage probability significantly reduces with an increasing SNR, where Coop. ARQ shows a lower message error probability than stronger coding. Interestingly, the gap between Coop. ARQ and Coding also increases by several orders of magnitude with higher SNR values. Furthermore, Coop. ARQ does not differ much in the total message error probability for different values of α.

We attribute the observed gap between Coop. ARQ and Coding to the realizable spatial diversity gain in case of cooperation. Moreover, the transmissions with Coop. ARQ experience a multiplexing gain, as the probability that multiple independent transmissions fail in the same communication cycle is relatively low. It is, thus, enough to reserve a small portion of the frame for Coop. ARQ to already significantly reduce the message error probability. Then again, a large slot for Coop. ARQ, i. e., $\alpha = 0.5$, does not significantly reduce the performance compared to a smaller retransmission slot, although the time for the original transmissions decreases, as



(a) Scenario (A): Low quality links to BS.



(b) Scenario (B): High quality links to BS.

Fig. 6. ϵ depending on D for different portions of α.

the larger retransmission slot compensates for the higher outage probability in the shorter transmission slot.

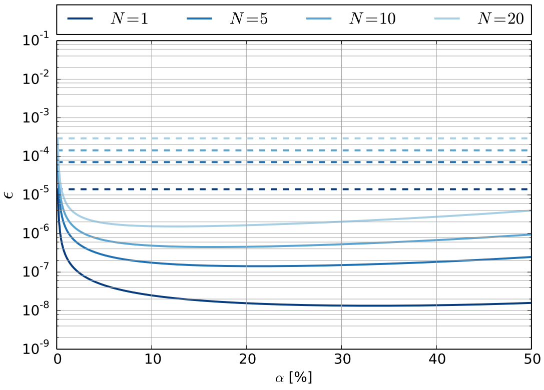
B. Impact of Message Size

We are further interested in how the message size influences the outage probability when applying either Coop. ARQ or Coding. Therefore, we analyze the message error probability in the two scenarios (A, B) for a variable message size D and $\alpha \in \{0, 0.1, 0.2, 0.5\}$. The results are shown in Fig. 6.

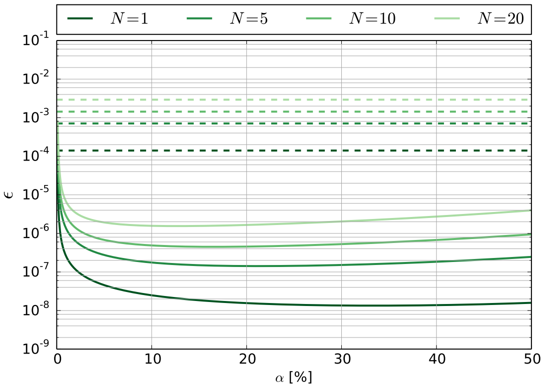
When Coding is applied, the error probability differs based on the average SNR between the stations, as the links to the base station are not used for transmission. However, for Coop. ARQ the results are almost identical in the two scenarios for message sizes up to 4096 bit, as the two scenarios complement each other in the chosen link qualities. Beyond a message size of 8192 bit, the message error probability drastically increases in all cases, as the probability of observing a sufficiently strong $\overline{\gamma}$ decreases. In this case, directly transmitting the message at a stronger coding outperforms cooperative retransmissions. On the other hand, small messages especially benefit from Coop. ARQ, as the reduced size allows to reduce the code complexity.

C. Duration of Retransmission Phase

An important aspect of incorporating Coop. ARQ is to determine the right duration of the retransmission phase. The BS does not know before the TDMA frame starts, how many messages will have to be retransmitted, and hence, how much time to reserve for retransmissions. The more sensitive the system reacts to changes in the duration of the retransmission phase, the worse will be the performance of a real system. Hence, we need to determine if there exists a global optimum α^{*}, which minimizes the total message error probability, and if there is such an optimum, on which parameters it depends. To get a first impression on the dependence on α, we changed α in the two scenarios with a different number of stations in the network, N. The obtained results are depicted in Fig. 7.



(a) Scenario (A): Low quality links to BS.



(b) Scenario (B): High quality links to BS.

Fig. 7. ϵ depending on α for a different number of transmissions N. The dashed lines indicate the respective reference for $\alpha = 0$.

The evaluation shows the existence of a relatively flat optimum depending on N. Both scenarios reveal that for a large N, a small α suffices. This can be explained by the higher multiplexing gain that occurs for a larger N. In this case, the probability that multiple transmissions fail in the same communication cycle is so low that a small α suffices. Then for a small N, a larger α allows for a stronger coding in the retransmission and is thus more beneficial.

D. Implications for the Medium Access Protocol

Given these evaluation results, we conclude that wireless communications with strong latency bounds should integrate Coop. ARQ with a comparably short retransmission phase (between 15% to 30% of the total frame) to achieve high reliability and thus to benefit from spatial diversity instead of solely relying on frequency diversity. This in turn allows to free these resources from increasing reliability of one network but rather establish multiple reliable networks in parallel. In this, the additional process complexity can be shifted to a local BS, to relieve resource-constrained devices, such as sensors, and to exploit the potentially higher hardware resources of the BS. Further, the results put an emphasis on the importance of applying device-to-device (D2D) communication, as anticipated in future 5G networks [9], to avoid an additional hop via the BS. The local BS should thus assume a mediator role, assigning transmission resources to the connected stations and intervening in the event of transmission errors.

V. RELATED WORK

In recent years, a considerable amount of publications has shown both analytically and experimentally the reliability gain of cooperative ARQ compared to traditional ARQ in different system settings, e. g., [10]–[12].

In [10], the authors show that the packet error rate (PER) is significantly lower with cooperative ARQ compared to a traditional ARQ approach. The authors explain these results through the inherent gain in spatial diversity of cooperative ARQ. Similarly, in [11], the results show that cooperation achieves a diversity order of $2L-1$, where L is the maximum number of (re)transmissions, while the non-cooperative scheme has only a diversity order of L, as it does not rely on independent fading channels for the retransmissions. These results indicate that a system design should favor cooperative over non-cooperative ARQ to increase the reliability, especially when bound to a short transmission latency. Furthermore, the authors of [12] analytically compare non-cooperative and cooperative ARQ to an adaptive coding scheme, under the assumption of strong channel correlation. Their results show that cooperative ARQ mitigates the negative effects of correlation and outperforms the other two variants, which confirms our performance results. In contrast to our work, however, all of these works do not investigate the effect of a strict time bound on the outage probability, i. e., when the time for retransmissions must be subtracted from total frame time to still meet the latency bound, thus leading to a weaker coding of the transmission.

Previous research already showed the practical relevance of the outage capacity when designing wireless communication systems [13], [14], as, in contrast to the ergodic capacity, it also takes delay constraints into account. By introducing an additional gap factor, the outage capacity model can be tailored to match imperfections of real physical layers [15].

VI. CONCLUSION

Achieving both ultra-high reliability and ultra-low latency in wireless communications is a challenging task, but nevertheless is required for mission-critical applications such as those found in industrial automation. One important step towards increasing the reliability of the communication, while not sacrificing timeliness, is through selecting the right redundancy schemes based on their gain for a given latency. In this paper, we analyzed the reliability gain of a system incorporating cooperative ARQ while meeting a very tight time bound. Therefore, we defined a system model for calculating the message error probability based on the outage capacity and assuming a flat, block-fading Rayleigh-channel. The analysis shows that COOP. ARQ with a comparably small retransmission phase reduces the message error probability by several orders of magnitude compared to the baseline approach of CODING, for the vast majority of scenarios and parameterizations. This approach is especially suited for resource-constrained devices, as the retransmission process is shifted to the more powerful BS. There, further reliability mechanisms, such as maximum ratio combining [16] or beamforming [17], could be included to strengthen the positive effects of cooperation.

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