# Unleashing latency-critical IIoT communication by virtue of cooperative sidelink-assisted DL transmissions

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*Abstract*—**Fifth generation wireless networks will play a crucial role in the digitization of factories. Smart factories demand ultra-reliable low-latency communication (URLLC) services to ensure a defect-free uninterrupted production system. In our earlier work, we have proposed a sidelink-assisted cooperative retransmission scheme, in which the neighbouring user equipments (UEs) assist an error-prone downlink (DL) transmission. The scheme benefits from making use of multiple independently fading device-to-device (D2D) links, and yields significant improvements in reliability, as analysed in our prior work. In this paper, we extend our study further to investigate latency for a realistic industrial IoT (IIoT) scenario modeled in a system-level evaluation platform. The D2D links established between communication nodes distributed over the factory area enable a reliable transmission by attaining larger Signal-to-Interference-Noise Ratio (SINR), yielding lower probability for higher latencies and reduced number of retransmissions. Our evaluations show that the cooperative scheme allows to save one retransmission for attaining 99.999% reliability and significantly reduces the queueing delays, thanks to a better usage of resources. The system-level evaluation proves our scheme to be an efficient tool to guarantee the reliability and latency requirements of URLLC in IIoT communication for smart factories at reasonable costs in resources.**

## I. INTRODUCTION

Driven by challenging quality of service (QoS) requirements and diverse deployment scenarios, research on 5G technology has advanced exceptionally in the past few years. The emerging distinctive service classes in 5G such as ultra-reliable low-latency communication (URLLC), enhanced mobile broadband (eMBB) and massive machine-type communication (mMTC) impose diverse QoS requirements on the system. Industry 4.0 is the fourth industrial revolution aiming at intelligent interconnected production systems. The wave of digitization with industrial internet-of-things (IIoT) will transform today's factories into smart factories [1]. To this aim, a 5G communication network can serve as a key enabler for a scalable and efficient industrial ecosystem, consequently uplifting the economic growth. Such automated systems demand a higher degree of reliability and uninterrupted connectivity that can guarantee stringent latency requirements. Reliable links with low-latency in a factory scenario are inevitable in order to ensure a steady production system [2]. Thus, URLLC communication is of high relevance when moving towards wireless connectivity in a factory, rendering URLLC as the key targeted service.

Cooperative schemes have gained attention as a useful means of exploiting the diversity gains in wireless networks [3] [4] [5]. The authors in [4] investigate on coverage probability in a cooperative retransmission scenario, in which the base stations selected based on their average received power levels and jointly transmit data in each transmission. The study concludes that temporal transmissions, when only one BS transmits in each time slot, provide a higher coverage probability than spatial cooperations, where BSs cooperate to transmit. Further, a cooperative retransmission method with the assistance of multiple relays has been introduced in [5]. The relays retransmit nonidentical packets to the destination that were transmitted unsuccessfully from either the source or other relays to the destination. A group-relay scheme is proposed to achieve a lower number of power-efficient retransmissions. In contrast to most of this research on cooperative relaying, our work benefits from the cooperation of multiple D2D UEs, that are exploited to simultaneously retransmit the identical packet, increasing the reliability of the transmission.

In [6], authors present a 5G enabled system architecture for IIoT and highlight the key technologies such as hybrid-ARQ (HARQ), scalable numerologies, mini-slots and grant-free radio access, as the fundamental bricks for URLLC type of communication. Thanks to the shorter transmission time interval (TTIs) enabled by the new frame structure including mini-slots, multiple retransmissions can be supported within a short latency budget. Furthermore, if HARQ schemes are employed, a large degree of diversity from retransmissions can be exploited in the decoding process at the receiver [2] [7]. In order to take maximum advantage of the retransmissions for URLLC, it is necessary to make sufficient diversity available in the network.

To this end, a cooperative retransmission scheme for URLLC communication has been proposed in our previous work [8]. Proved in our analytical study, the cooperative scheme pinpoints significant improvements in reliability, continuously scaling by one order of magnitude with the degree

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of diversity made available. In order to unveil the latency behaviour of this scheme, the focus of this paper will be on investigating the latency performance. Since all components influencing the latency in a real system, such as processing delay, segmentation delay, and especially queuing delay, cannot be easily modeled by an analytical study, here, we evaluate the cooperative scheme in a realistic system-level environment. The evaluation will be performed considering different user selection and grouping schemes. The primary focus of this research is to exploit multiple independently fading D2D links for retransmissions aiming at high reliability and low-latency. The performance of this scheme in terms of latency and number of retransmissions is evaluated based on a realistic scenario modeled and simulated in NS-3 simulator [9] [10]. The results clearly highlight gains in terms of latency and reliability, displaying an improved SINR performance, particularly with the examined user grouping schemes. Furthermore, we observe a substantial reduction in the number of retransmissions as an effect of reliable transmissions via sidelink, yielding a positive effect on the DL queueing lengths, which gives room for faster initial transmissions.

## II. Cooperative retransmissions via sidelink

### A. Network scenario

An Industry 4.0 factory scenario is shown in Fig. 1, assuming multiple automated guided vehicles (AGVs) moving around in the factory, representing mobile communication nodes. These large number of AGVs supporting a direct connection (AGV ⟷ AGV) form various independently fading D2D links via sidelink. We consider a DL multicast transmission to a target AGV. In order to enable neighbour AGVs to overhear the packet, such that they can assist the target AGV by forwarding the received packet if retransmissions become necessary. The cooperative retransmission scheme mainly aims at exploiting the diversity of independent D2D links between AGVs to improve reliability and latency. In the case of an unsuccessful reception of the DL data, the target AGV can seek a cooperative retransmission from its neighbours. The detailed workings of the proposed scheme is illustrated in the next section. Assuming the target AGV is surrounded by sufficient neighbours, the cooperative scheme proves to be an efficient solution to attain the reliability target as shown in our recent paper [8] and the latency critical constraints further targeted in this work.

### B. Cooperative retransmission scheme

We consider a multi-cell network for URLLC communication, represented in Fig. 2, where the cell consists of a base station (BS), target UE (node A) and neighbour UEs. The BS multicasts URLLC packets intended for node A to a group of users including node A, allowing the neighbour UEs of node A to assist in potential further retransmissions. The link between the UE and the BS may get obstructed by e.g. some other AGV moving around the factory. Such obstruction may cause link failure, which can be critical for a URLLC communication, and hence needs to be circumvented.

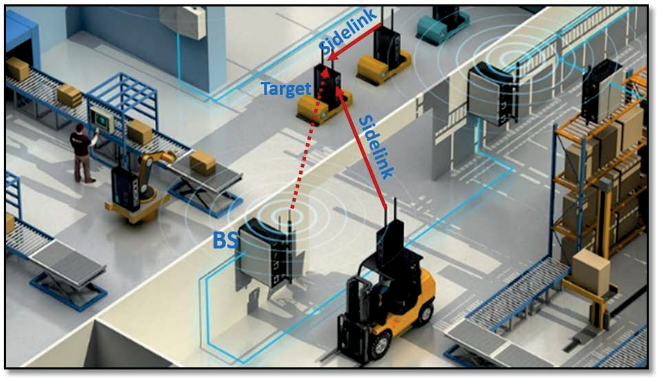

Fig. 1. Factory automation scenario

The key idea is to exploit the D2D links present in the network to support a DL transmission. If a need for retransmission arises, multiple UEs may retransmit the same packet in the same resource by using transmit diversity schemes. Here, the transmit power is shared equally among all the users cooperatively retransmitting at the same time. Independently fading links are assumed between the neighbours and node A, which can be utilized for retransmission by applying transmit diversity schemes in a distributed fashion, such as distributed space-time block codes (STBC) [11], [12] or cyclic delay diverstiy (CDD) [13]. These schemes enable a constructive addition of multiple versions of the same signal propagated via different D2D paths, where CDD requires less stringent synchronization between the nodes compared to STBC. Since each of these D2D links experiences different small-scale fading and shadow fading caused by bypassing AGVs in particular, the constructively added signal at the receiver benefits from the diversity of these independent channels.

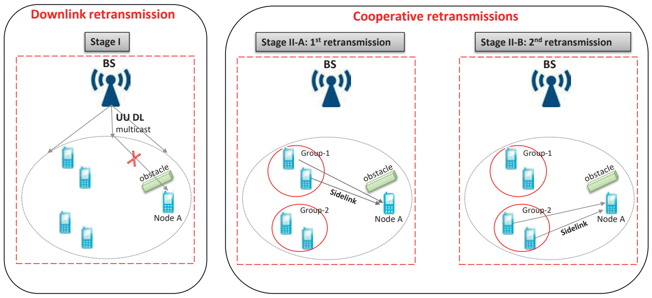

Fig. 2. Group based cooperative retransmissions

Group-based cooperative retransmission scheme is demonstrated in Fig. 2. In stage I (DL transmission), in case of a disrupted link to node A followed by an unsuccessful reception of a URLLC packet from the BS, node A can request a retransmission via sidelink from its neighbours. In stage II (Cooperative retransmission), UEs in a predefined group containing all eligible UEs for retransmissions, can be the potential assisting UEs to node A. The UE eligibility depends on the successful reception of the DL multicast packet. As the industrial scenario is densely populated by UEs, at least a few neighbours will receive the DL packet successfully in real-time. Therefore, we assume the probability of successful reception by the neighbour UEs to be unity. In order to exploit diversity gains to the fullest, the cooperative scheme allows selection of different user groups for retransmissions, as illustrated in the figure, where two different user groups are selected during the first retransmission (stage II-A) and second retransmission (stage II-B) respectively. The cooperative HARQ transmission scheme enables a constructive addition of the powers of the channel coefficients from all these individual links, as enabled by STBC or CDD scheme.

### *C. UE selection and grouping methods*

A set of users is formed based on the D2D distance or link quality defined by average signal-to-noise ratio (SNR) between the neighbour UEs and the target UE ($u_T$). A user set may contain all the users in the cell or a subset of users from the cell. Once the user set $U$ for the target UE ($u_T$) is established, the next step is user selection for retransmission. For every retransmission, the process of user selection is triggered. The following three methods are proposed and evaluated for UE selection.

Let $n$ be the number of neighbour users to target UE $u_T$, eligible for retransmission (size of the user group), $k$ be the actual number of users cooperatively retransmitting and $U = \{u_1, u_2, \ldots, u_n\}$ be the set of eligible neighbours (user set). In this evaluation, we select $k$ in $\{1, 2, 3\}$ and $n$ is the number of users eligible for retransmission. However, determining the precise number of users ($k'$) needed for retransmission is left for future investigation.

*1) Method 1: Random-User Selection:* For the sake of simplicity, here, a user set ($n$) consists of all active users in the cell. In order to perform a retransmission via sidelink, $k$ users are selected randomly from the already created set. Random-user selection is a simple method taken as a reference, whereby each UE in the set has an equal chance of being selected for retransmission. In this scheme, $k$ randomly selected users from all the users in the cell transmit cooperatively.

*2) Method 2: Best-User Selection:* The target UE selects the users with the best average D2D channel quality to itself for retransmission, assuming that each user is aware of the average channel quality to its neighbours. Average SNR is considered as a measure to determine the channel quality of these D2D links. Unlike the random user selection scheme, this selection method is more systematic.

Here, the set of users $U$ contains all the $n$ users available in the cell. For every retransmission, the $k$ best users are selected to transmit cooperatively, hence each retransmission is usually carried out by the same set of users.

*3) Method 3: User-Combination Selection:* In this method, a subset of best users is created based on their average SNR, from the user set $U$ which contains all users in the cell. Different combinations are formed from the preselected subset of best users and for every retransmission, a unique combination is selected. Due to this distinct user selection for each retransmission, the identical signal is sent via multiple independently fading transmission paths in each retransmission. This scheme allows the use of the diversity from the best D2D links first, while considering additional diversity sources in the successive retransmissions.

The grouping by user-combination technique is illustrated as follows: Let $m$ be the preselected subset of best users from $n$ available users in the cell and $k$ be the number of users present in each combination transmitting cooperatively. According to permutation and combination theory, there are a total of $(m!/k!(m-k)!)$ possible combinations. For instance, $m = 3$ and $k = 2$, considering user set $U = \{u_1, u_2, u_3\}$, the following user combinations $(u_1, u_2), (u_1, u_3), (u_2, u_3)$ are created. For the first retransmission, the best user pair is selected ($(u_1, u_2)$), then using the permutations, a user set containing the best user combined with others from the set is selected, and so on, allowing a unique selection for all three retransmissions.

## III. SYSTEM DESIGN

In this study, we evaluate the performance gains of the cooperative scheme in a realistic environment, considering different user selection methods in a multi-cell scenario. NS-3, a discrete-event driven network simulator, has been used for performance analysis during this work [9] [10] [14].

We consider a multi-cell network topology constituting 7 tri-sector sites with an inter-site distance (ISD) of 200 m and each sector being referred to as a cell. The location of sites is fixed as per hexagonal geometry, with the center site being at coordinate (0,0) and the placement of 21 cells respectively. We assume a bandwidth of 20 MHz, consisting of 100 RBs in the time-frequency domain and 420 active users in the multi-cell scenario. The UEs are dropped uniformly around the 21 cells and are attached to the cell with strongest signal based on the UE position, yielding 20 users per cell on average. The mobility of the UEs/AGVs in our factory environment is considered at a pedestrian speed of 3 km/h. In this evaluation, multiple independent user constellations (user drops) are simulated and averaged, to ensure sufficient statistics. Other simulation parameters are described in Table I.

For DL propagation, the Cost-231 Hata path loss model simulating the urban environment with statistical shadow fading is applied, while sidelink propagation is modeled by the 3GPP-Winner II channel model [15] [16], which provides accurate and realistic channel properties suitable for evaluating the D2D links [17]. Wireless channels between every D2D pair are assumed to undergo independent frequency selective Rayleigh fading.

We apply a channel and QoS-aware scheduler (CQA), a DL scheduling method which considers the head-of-line (HOL) delay, the guaranteed bit rate (GBR) and channel quality over different subbands [18]. The scheduler can be split into two phases, time domain (TD) and frequency domain (FD) scheduling, which are jointly applied. In the TD (at each TTI), users are grouped based on HOL delay as priority in order to enforce that the FD scheduler considers first the

TABLE I
SYSTEM CONFIGURATION

| **Parameters** | **Value** |
|---|---|
| Layout | Hexagonal grid |
| Bandwidth | 20 MHz |
| Carrier frequency | 2.3 GHz |
| No. of cells | 21 |
| No. of UEs | 420 |
| Inter-site distance | 200 m |
| TTI size | 250 $\mu$s |
| Packet size | 200 bytes |
| Traffic load (per cell) | 5 Mbps |
| gNB transmit power | 23 dBm |
| UE transmit power | 0 dBm |
| UE mobility | 3 Kmph |
| Antenna system | 2*2 MIMO |
| UE distribution | Uniformly |
| DL channel | Cost-231 Hata channel model |
| D2D channel | 3GPP-Winner II channel model |

flows with highest delay, so as to reduce the waiting time for transmissions. Furthermore, the FD scheduler schedules the users in a proportional fair manner. Influenced by the link adaptation strategy in [19], the adaptive modulation and coding scheme (AMC) has been altered to support 99.999% reliability after three retransmission attempts, by adjusting the target block error rate (BLER) for URLLC. Here, HARQ retransmissions are carried out on the basis of LTE DL HARQ timings using 8 HARQ processes, which are prioritized over other transmissions. Hence, the HARQ round trip time (RTT) is 2 ms with the TTI size of 250 $\mu s$ and 8 HARQ processes. As every retransmission contains the same information, chase combining at the receiver combines the received bits with the bits received in previously received (re-)transmissions.

## IV. PERFORMANCE EVALUATION

We evaluate the performance of the cooperative retransmission scheme compared to the conventional DL retransmission scheme. The simulation configuration and parameters used are elaborated in Section III and summarized in Table I. We consider a scenario mainly targeting DL multicast transmissions, where HARQ retransmissions are modeled either via DL or via D2D. Here, the DL transmissions are the first transmission attempts for each packet. We do not explicitly model the blocking of DL, however, it is reflected by the statistical shadow fading model implemented in the Cost-231 Hata model. A fully loaded task-sensitive network is considered, with all UEs transmitting in UL, and DL transmission to all UEs in the network, thus engaging most of the UEs in cooperative retransmission. Additionally, we assume the sidelink to be in-band such that the total bandwidth is shared (time division duplex (TDD) mode), where D2D communication uses the UL resources and experiences interference from UL and D2D transmissions in the neighbouring cells. The latency of successful receptions has been measured at the medium access control (MAC) layer, which inherently includes the queueing and processing delays. Fig. 3 represents the latency performance for the different cooperative user selection methods. The plateaus in the curve are caused as an effect of the HARQ RTT and queueing delay, and highlight the successive (re-)transmission attempts. The leftmost plateau represents the first transmission, followed by other plateaus for the consecutive retransmissions, respectively. The performance attained with the traditional DL HARQ scheme (black curve), where all retransmissions are performed via DL, is taken as a reference for the analysis.

In this evaluation, a fixed amount of power is allocated for each retransmission to ensure a fair comparison, i.e. the total constant power of $0\ dBm$ is always shared equally among all $k$ users transmitting cooperatively. As illustrated in Section II-C, $n$ and $k$ are chosen based on the grouping scheme. For the first two methods, i.e. method-1 (random-user) and method-2 (best-user selection), the number of users retransmitting ($k$) is selected from eligible neighbours ($n$) i.e. all users in the cell, where $n = 20$. In the first case, when applying the random-user selection method with $k = 1$ (dashed red curve), $k = 2$ (dashed green curve), $k = 3$ (dashed magenta curve), it can be observed that the probability of higher latencies reduces continuously with the increasing number of cooperating users, thanks to the additional diversity gains. Analyzing the random selection method is helpful to highlight the effects of diversity even using such a simple no-brainer method. At least three cooperating users ($k = 3$) are needed to observe gains better than the traditional DL HARQ scheme. Hence, for this case, we can conclude that there is always (at least) one user who can provide a link that is substantially better in quality than the DL. In method-2 (best-user selection), the probability of retransmissions is reduced by one order of magnitude in comparison to the traditional DL retransmissions. As an effect of the close proximity of D2D UEs, yielding a better link quality, results in higher SINR which translates to a higher probability of successful decoding and hence more reliable transmission compared to the DL. Increasing the number of cooperative users to $k = 2$ (solid green curve) and $k = 3$ (solid magenta curve), indicates a further improvement in the delay performance (after first plateau) for the second and third retransmission compared to best-user selection $k = 1$, highlighting the gains from additional diversity.

As a consequence of replacing retransmissions via DL with retransmissions via D2D; less number of DL resources are needed for the DL transmissions, since retransmissions via sidelink are more reliable and less required due to the better SINR conditions. As depicted in the figure, the level of first plateau is lower for the cooperative scheme compared to the conventional DL scheme. This implies fewer resources being used on average due to a lower number of retransmissions, in turn causing lower interference compared to DL HARQ and, hence, a lower probability for a failed first transmission. Further, in method-3 (user-combination scheme), different user combinations are considered for retransmissions (blue curve); where, a subset of $m = 3$ best users is selected

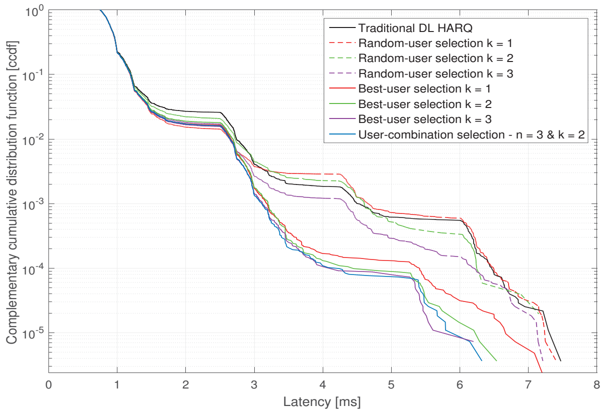

Fig. 3. Latency performance: Comparing different user-selection methods

from $n = 20$ available users in the cell. User combinations containing $k = 2$ users are formed as explained in Section II-C3: $(u_1, u_2), (u_1, u_3), (u_2, u_3)$, with $(u_1, u_2, u_3)$ being in descending order of average SNR. This implies that always two users transmit, but in each retransmission attempt a different pair is picked from the user set of $m = 3$ users, to make use of the full diversity provided by the $m$ best users. Interestingly, the user-combination method performs better than the best-user method with $k = 2$, highlighting the gains from additional diversity made available by adding a third user to the set of $m$ best users. Furthermore, method 3 with $k = 2$ performs in essence equivalently to the best-user selection scheme with $k = 3$, while being less complex. For instance, the complexity due to synchronization between UEs is comparatively reduced with a lower number of users ($k$) cooperatively transmitting.

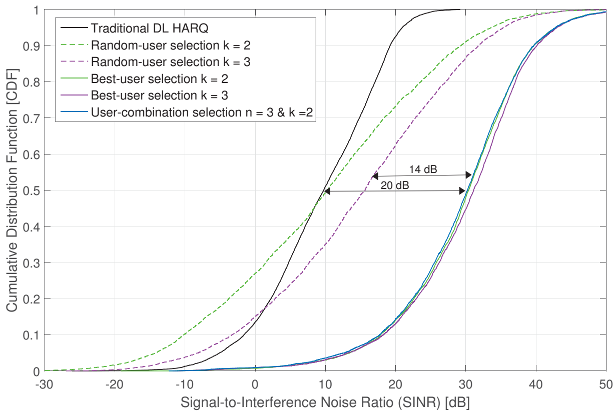

Fig. 4. SINR performance: Comparison of SINR for retransmissions with different user-selection methods

To get further insights into the behavior of the different user-selection schemes, we evaluate the SINR conditions for retransmissions (Section II-C), demonstrated in Fig. 4. The SINR at the receiving target UE reflects the ratio of useful signal from the cooperatively retransmitting UEs composed by constructive addition of their channel gains and the interference caused from the users in all adjacent cells. The performance for DL HARQ (black curve) attains the lowest median SINR at 10 $dB$ with a steeper slope, where the shape reflects the typical effects observed from fading in DL transmission. Here, the SINR varies in a range of 30 $dB$, which is attributed to large and small scale fading. Next, with the random-user scheme, we observe a slightly better median SINR which improves with $k$ cooperating users. However, the random selection of users leads to a broader slope of the curve, since UEs at unfavorable locations in the cell, such as the other end of the cell, can participate in the cooperative transmission. This affects the SINR for certain UEs, which is reflected in the left tail of the curve, showing a worse performance than the DL HARQ scheme. The results display larger gains in terms of SINR for the best-user and user-combination schemes, with an increase in SINR by 20 $dB$ and 14 $dB$ on average, compared to the traditional DL HARQ and cooperative random-user selection, respectively. These two schemes with $k = 2$ users are comparable in their achieved SINR, but the user-combination scheme attains better latency performance (Fig. 3) by virtue of additional diversity gains. We observe a further minimal increase in SINR with the best-user selection $k = 3$, which, however, does not translates to a substantial performance gain in latency. This indicates that the increased SINR cannot be beneficially utilized, since the packet can already be successfully decoded with the SINR attained by $k = 2$ cooperating users.

Subsequent to the huge SINR margin of 20 $dB$ offered by the favourable cooperative schemes (method 2 and method 3), we expect a possibility of further transmit power saving for the cooperating UE, while maintaining the delay performance. This suggests the beneficial application of power control schemes, taking into account the sidelink pathloss based power constraint for the cooperative transmissions. This serves as the motivation for our ongoing research work on power control schemes for cooperative retransmissions and the findings will be presented in our upcoming publication.

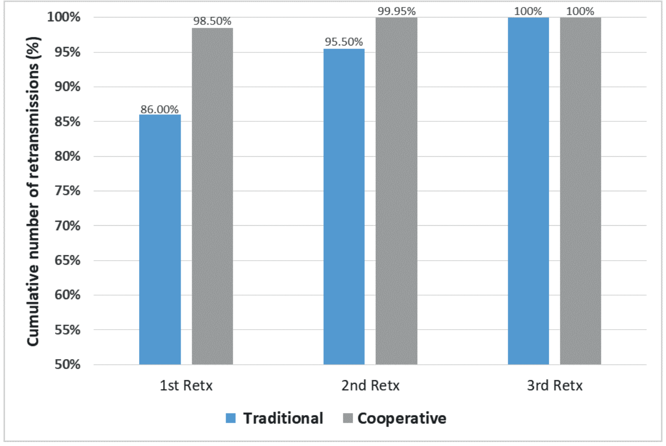

Fig. 5. Successful retransmissions relative to the total number of retransmissions for each Retx attempt.

Further, we analyze the effect of the cooperative scheme on the number of required retransmissions, as demonstrated in Fig. 5. In this analysis, we consider only the cases where the first transmissions failed and retransmissions were required, which amounts to $2\%$ of the total transmissions for the user-combination cooperative scheme, as observed by the first plateau settling at $2 * 10^{-2}$ in Fig. 3. For all retransmissions, here, we evaluate the accumulated success rate of the succeeding 1st, 2nd and 3rd retransmissions (Retx). With the cooperative scheme, the majority of the retransmissions $(98.5\%)$ are successfully received in the first retransmission (1st Retx) attempt. Whereas, with the traditional DL scheme, the success rate of the first retransmission attempt is $86\%$, being significantly lower. To calculate the overall reliability of the 2nd retransmission, which is constituted from the probability for a retransmission $(1 - 0.98 = 2 * 10^{-2}$, see above) times the probability of 2nd retransmission having failed $(= 1 - 0.9995)$, we obtain the probability that first transmission plus the two retransmissions are erroneous, which is the negated value of the reliability, is computed as follows:

$$(1 - 0.98) * (1 - 0.9995) = (1 - 0.99999)$$

Hence, the attainable reliability with maximum two retransmissions is $99.999\%$, representing that two retransmissions are sufficient for a successful reception with a reliability of $99.999\%$. As it can be read from Fig. 3 (blue curve), a maximum latency of 6 ms is needed for successful second retransmissions. Whereas, in the traditional DL scheme, three retransmissions are required to attain the reliability of $99.999\%$ with a latency of around 7.5 ms. Thus, the analysis reveals that the cooperative scheme can save one retransmission, which in essence reduces the latency and, as indicated earlier, shortens the queueing delays, which also yields an improved usage of the available resources.

## V. CONCLUSION

In this paper, we have evaluated the latency performance at system-level for a cooperative scheme proposed in our earlier work. In a smart factory environment, the cooperative scheme benefits from several independently fading D2D links available, which can be exploited by applying transmit diversity schemes. In this work, we extend the study for latency critical communication and evaluate the proposed scheme with respect to different user grouping and selection methods for retransmissions, in a realistic system-level IIoT environment. The results show higher SINR gains for retransmissions with cooperative schemes in comparison to traditional retransmissions via DL. By virtue of which, a significant reduction in probability of retransmissions of up to one order of magnitude compared to DL HARQ is observed. Additionally, the analysis on the number of retransmissions highlights that the cooperative scheme can attain a reliability target of $99.999\%$ already after two retransmissions. In contrast, the conventional DL retransmission scheme needs three retransmissions to achieve this reliability target. As a result, we can save one retransmission with the cooperative scheme, which improves latency and shortens the queueing delays, resulting in substantially improved use of available resources.

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