Successive Interference Cancellation-Aided NOMA in URLLC with Time and Frequency Diversity

Luis Henrique de Oliveira Alves, João Luiz Rebelatto, Glauber Brante and Richard Demo Souza

Abstract— **Ultra-Reliable Low-Latency Communication (URLLC), contemplated in the Fifth-Generation New Radio (5G NR) standard, is considered essential to a broader implementation of latency-sensitive future technologies. Grant-Free (GF) schemes have been proposed towards reducing latency in URLLC, but the increased probability of collision conflicts with the reliability requirement. Aiming at reducing the impact of collisions, a transmission scheme using Non-Orthogonal Multiple Access (NOMA) and Successive Interference Cancellation (SIC), along with time and frequency diversity, is studied in this paper. Our results indicate that the proposed scheme considerably improves the system performance when compared to the destructive collision model commonly adopted in literature.**

Keywords— **Ultra reliable low latency communications, non-orthogonal multiple access, successive interference cancellation, time-frequency diversity.**

I. INTRODUCTION

The Fifth-Generation New Radio (5G NR) standard can be divided into three heterogeneous use cases, namely enhanced Mobile Broadband (eMBB), massive Machine Type Communications (mMTC) and Ultra-Reliable Low-Latency Communication (URLLC) [1]. While eMBB focuses on high transmission rates and mMTC aims at dealing with a massive number of devices, URLLC requires a reliability of at least 99.999% and latency no higher than 1 ms, being of particular interest in areas such as automotive industry with vehicle-to-anything (V2X) communications and Industry 4.0 [2].

However, to reconcile the strict latency and reliability requirements is a major challenge in URLLC, as there is an inherent trade-off between them. Uplink design in previous generations of mobile communications, as in Long Term Evolution (LTE), has considered an Orthogonal Frequency Division Multiple Access (OFDMA) grant-based approach to deal with the connection between User Equipment (UE) and the Base Station (BS) [3], specified in [4]. In this model, channel access is controlled by techniques based on transmission scheduling, where the BS is capable of reserving frequency subchannels for the duration of the transmission of each UE. Although this is effective in avoiding collisions, in orthogonal access-based schemes the UEs experience latency due to prior-to-payload interactions with the BS, which contrasts with the latency requirements of URLLC [5].

Moreover, dedicated orthogonal frequency subchannels may be an inefficient use of the spectrum, given the increasing expected load (number of users) [6]. In this scope, Non-Orthogonal Multiple Access (NOMA) Grant-Free (GF) based systems may provide a viable alternative [6], [7], as they skip any scheduling in order to reduce access latency and promote higher spectral efficiency. Even though NOMA GF transmissions can more efficiently share network resources through contention-based access in scenarios with random and sporadic access [8], the approach exposes the system to collisions, which can harm the network reliability when the load is sufficiently high [3]. Other solutions include hybrid approaches, as in [9], [10], where the UEs transmit in phases of dedicated and shared frequency resources. This solution may diminish the effect of collisions, but in case of a high load the UEs would have to wait for availability before transmitting, which could put the latency beyond URLLC requirements. Nevertheless, in [6], [7] it is shown that the GF alternative can outperform scheduled solutions for the given latency requirements. Therefore, techniques based on mitigating the effects of collisions on overall system performance may be a more practical approach to a more efficient network design.

Repetition schemes are commonly used for reducing the performance impact of collisions. They are classified as reactive, proactive and K_u-repetition schemes [7], [8], [11]. Both reactive and proactive techniques allow feedback from the BS after each packet transmission within a time-slot. In the K_u-repetition scheme, the UE transmits K_u replicas of the payload before receiving a feedback from the BS. After the feedback, the UE decides whether it is necessary to realize further retransmissions on the next time-slot. Due to the smaller overhead, we focus on K_u-repetition, which has been studied for time [8], frequency [11] and time-frequency [12] diversity schemes in URLLC, by considering advanced receivers with Multiple User Detection (MUD) capabilities.

Even though repetition schemes are very effective at low loads, such approach may be not beneficial for dense environments. In the latter scenario, the treatment of collisions at the receiver becomes very relevant. Investigations in this line can be found, for instance, in [11], [12], but considering a destructive model, where collided packets are unrecoverable. Such assumption can be too pessimistic [8], specially at high load scenarios. Instead, Successive Interference Cancellation (SIC), combined with a soft collision model, is a viable alternative [8], [13]. A SIC-based receiver allows for more decoding attempts, which may increase the probability of

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success at the cost little latency increase.

With the high load limitations of NOMA GF, setting an appropriate value for K_u is vital to achieving URLLC performance: for a fixed number of UEs, a larger number of replicas implies higher collision probability. The optimal value of K_u is obtained in [12] through particle swarm optimization. It is also found that time-frequency diversity yields better results in terms of supported number of devices for a fixed 99.999% reliability requirement of URLLC. The adopted system model considers Maximal-Ratio Combining (MRC) for the received replicas which have not collided. The use of the destructive hard-collision assumption, however, may underestimate the potential of the time-frequency diversity scheme.

The probability density function of the available diversity for a fixed number of interfering independent transmissions is derived in [11] for a system which considers the destructive hard-collision assumption. A MUD scheme is discussed, but the use of a non-destructive collision model is suggested as future work. Also, the considered system model operates with frequency combining only. Finally, a receiver based on both MRC and SIC is considered in [8] for a time-frequency combining scheme. However, that model considers perfect cancellation of previously decoded packets, which requires prior-to-payload interactions between UEs and the BS, increasing latency.

This paper evaluates the performance of URLLC in a NOMA uplink scenario with random GF access, by considering a K_u-repetition approach with time-frequency diversity combining through MRC and a non-destructive treatment of collisions based on SIC. We obtain, through computer simulations, the performance of the aforementioned system in terms of reliability (measured by the loss ratio). The use of SIC allows a less pessimistic treatment of collisions than that of [11], [12], which considers them as being destructive. Also, our approach differs from other previous works, such as [7], [9], [11], [13]–[15], due to the use of a time-frequency diversity combining scheme at the BS receiver through MRC. We show that the novel proposed MRC-SIC scheme is capable of improving the reliability when compared to those whose implementation is based on the destructive collision assumption. Since the perfect cancellation of previously decoded packets consideration from [8] would require prior-to-payload activity detection, we consider a more practical GF receiver, where SIC is performed without prior knowledge regarding collided signal identification. We show that our approach can be viable in reaching URLLC reliability in a random access scenario.

The rest of this paper is organized as follows: Section II presents the system model and the benchmark MRC-DCM scheme. The proposed MRC-SIC receiver is presented in Section III, while Section IV presents some simulation results. Finally, Section V concludes the paper.

II. PREMILIMARIES

A. System Model

We consider an uplink scenario where a set of M active URLLC devices, indexed by $m \in \{1, \dots, M\}$, have independent information to transmit to a common BS during a given time-slot. Furthermore, M is randomly obtained according to a Poisson Point Process (PPP) with arrival rate λ. The M active devices are considered to be distributed randomly in a fixed radius around the BS, as illustrated by Fig. 1.

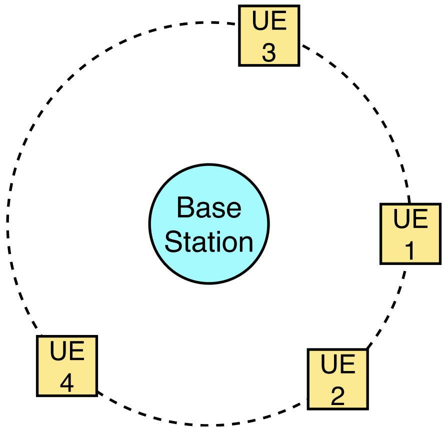

Fig. 1. Equidistant random distribution of $M = 4$ UEs around the BS.

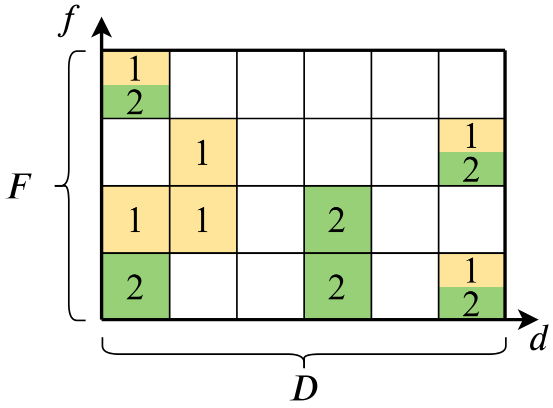

Fig. 2. Example of a 2-UE scenario with $F = 4$ subchannels and $D = 6$ mini-slots. Each UE transmits in $K_u = D_u \times F_u = 3 \times 2 = 6$ locations.

By considering that a time-slot is further divided in D mini-slots, indexed by $d \in \{1, \dots, D\}$, and that the overall bandwidth is split into F subchannels, indexed by $f \in \{1, \dots, F\}$, we assume a time-frequency replication scheme where each device retransmits copies of its packet in $D_u \leq D$ mini-slots and $F_u \leq F$ subchannels per mini-slot, in a uniformly distributed random GF fashion. This is depicted in Fig. 2, for a scenario with $M = 2$, $F = 4$, $F_u = 2$, $D = 6$ and $D_u = 3$.

Hereinafter, we refer to a given pair (f, d) of subchannel and mini-slot as a *location*. After the transmission of replicas in $K_u = D_u \times F_u$ locations of the time-slot, the UE waits for feedback from the BS before deciding whether or not to transmit another K_u repetitions in the next time-slot.

For convenience, we define $\boldsymbol{\varphi}(m, d)$ as an indicator function whose output is a $\mathbb{N}^{1\times F}$ vector composed of binary elements that indicate the existence of collision-free packets in the d-th time slot associated with the m-th UE, for each frequency channel. For instance, $\boldsymbol{\varphi}(1, 2) = [0\ 1\ 1\ 0]$ and $\boldsymbol{\varphi}(2, 4) = [0\ 0\ 1\ 1]$ in the scenario depicted in Fig. 2.

The channel fading is assumed to follow a quasi-static Rayleigh distribution, where the channel coefficient remains constant during a given time-slot and subchannel, and then changes in an independent and identically distributed (i.i.d.) fashion between time-slots and subchannels. Thus, the overall channel matrix in a given time-slot can be represented by $\mathbf{H} = [\mathbf{h}_1\ \mathbf{h}_2 \cdots \mathbf{h}_M]$, where $\mathbf{H} \in \mathbb{C}^{F \times M}$ and $\mathbf{h}_m = [h_{m,1}\ \cdots\ h_{m,f}\ \cdots\ h_{m,F}]^T$ is the channel coefficients of the m-th UE, such that $h_{m,f} \sim \mathcal{CN}(0, \Gamma)$ [1]. The average Signal-to-Noise Ratio (SNR) of each transmitted packet, denoted by Γ, is assumed to be the same for all UEs. Finally, the UEs are assumed not to have any channel state information (CSI), while the BS is considered to be provided with full CSI.

B. MRC-Destructive Collision Model (DCM)

In this work we consider as benchmark the MRC-DCM scheme as in [12], where the packets are declared lost in the case of collisions, *i.e.*, when two or more unknown packets are transmitted in the same location (at the same mini-slots and using the same subchannel). Considering the example provided in Fig. 2, the packets transmitted in the last mini-slot would be considered unrecoverable [12], such that one would have $\boldsymbol{\varphi}(m, 6) = [0\ 0\ 0\ 0]$ for both devices, and would, therefore, not be used in the MRC.

In a given time-slot d, the collision-free replicas are then jointly combined at the receiver through MRC, in a cumulative fashion that encompasses all the previous replicas received up to the d-th time-slot. Therefore, the post-processing SNR for the m-th UE[1] at mini-slot d is obtained as [17]

$$\mathrm{SNR}_m(d) = \Gamma \sum_{k=1}^{d} \left(\boldsymbol{\varphi}(m,d) \circ \mathbf{h}_m^{\dagger}\right)\mathbf{h}_m, \qquad (1)$$

where $\dagger$ indicates the conjugate transpose, and $\circ$ denotes the element-wise Hadamard product [10]. Thus, in the d-th mini-slot, the packet from the m-th UE is not decoded when its current accumulated SNR leads to a mutual information lower than the attempted transmission rate R (in bits/s/Hz). This event, referred to as $\mathcal{O}_m^{\mathrm{MRC}}(d)$, has probability

$$\Pr\left[\mathcal{O}_m^{\mathrm{MRC}}(d)\right] = \Pr\left[\log_2\left(1 + \mathrm{SNR}_m(d)\right) < R\right]. \qquad (2)$$

Finally, the packet of the m user is declared to be in outage in the MRC-DCM scheme when is it not decoded in the last time-slot, which happens with probability

$$\Pr\left[\mathcal{O}_m^{\text{MRC-DCM}}\right] = \Pr\left[\mathcal{O}_m^{\mathrm{MRC}}(D)\right], \qquad (3)$$

where $\Pr\left[\mathcal{O}_m^{\mathrm{MRC}}(D)\right]$ comes from (2).

III. MRC-Successive Interference Cancellation (SIC) Model

In addition to MRC-DCM, we propose a non-destructive scheme, aiming at possibly recovering the packets in locations with collisions. More specifically, our proposed MRC-SIC scheme adds one more independent decoding stage[2] to the MRC-DCM scheme, where the receiver attempts to decode the collided packets in each location through SIC, as in Fig. 3.

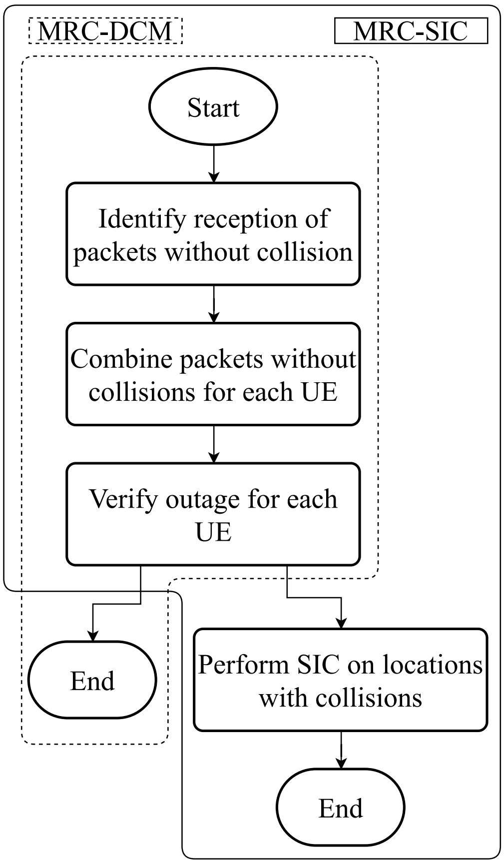

Fig. 3. MRC-DCM and MRC-SIC receiver processes, activated every mini-slot.

The proposed MRC-SIC receiver operates, then, in two distinct phases. The first phase of the proposed scheme operates analogously to MRC-DCM, where the collision-free packets are combined through MRC, with the outage event being obtained from (3).

The SIC is performed as a sequential process, where, for each location where there are collided signals, the BS attempts to decode the signal with the highest instantaneous SINR, while treating the other users as interference. Upon correctly decoding such signal, it is then removed from the superimposed signal and the BS then tries to decode the following signal in decreasing order of instantaneous SINR. This process continues until the occurrence of the first outage (if any), situation in which the other users with lower instantaneous SINR are also declared to be in outage in that particular location [18], [19]. Note that for the last remaining signal in a collided location, where all others have been cancelled, the receiver can attempt to decode as if no collision had occurred.

Let $\mathcal{F}_{m,d} \subset \{\emptyset, 1, \cdots, F\}$ be the subset of channels with collisions, including the packet from the mth user, in the dth time-slot. The number of elements in $\mathcal{F}_{m,d}$ is given by $|\mathcal{F}_{m,d}| = F_{m,d}$ and indexed by $f' = \{1, \ldots, F_{m,d}\}$. We define as $\mathcal{O}_{f'}^{\mathrm{SIC}}(d)$ the event that the BS is not capable of recovering the packet of the mth user in location $(\mathcal{F}_{m,d}(f'), d)$ after performing SIC. Note that, although the fading is assumed

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[1] Note that the same results are valid to all the users, due to the equal average SNR assumption adopted in this work. This can be supported in practice, for example, by means of an adaptive power control mechanism where the UEs receive feedback from the BS and are then able to adapt their transmit power in order to compensate the unbalanced path-losses [16]. However, it is worthy mentioning that the fading cannot be compensated.

[2] One could also consider a joint MRC-SIC decoding, where both stages are jointly performed. However, the evaluation of such scheme is left as a future work.

TABLE I
SIMULATION PARAMETERS.

`Parameter`	`Value`	`Reference`
F	6	`[21]`
D	14	`[8]`
R	0.5 `bps/Hz`	
δ	1.0×10^{-10}	

to be i.i.d. in time and frequency, $\Pr\left[\mathcal{O}_{f'}^{\text{SIC}}(d)\right]$ does vary to different locations since it depends on the decoding order that user m experiences in the SIC process, as well as on the number of interfering nodes, which is a random variable. Having in mind that the outage events in different locations are independent, the overall outage probability of the proposed MRC-SIC scheme is formulated as

$$\Pr\left[\mathcal{O}_m^{\text{MRC-SIC}}\right] = \Pr\left[\mathcal{O}_m^{\text{MRC}}(D)\right] \Pr\left[\prod_{d=1}^{D} \prod_{f'=1}^{F_{m,d}} \mathcal{O}_{f'}^{\text{SIC}}(d)\right] \quad (4)$$

Due to the intricate form of (4), it is difficult (if possible) to obtain a closed form expression to the outage probability of the proposed MRC-SIC scheme. Thus, in what follows, we evaluate $\Pr\left[\mathcal{O}_m^{\text{MRC-SIC}}\right]$ by means of computer simulations.

A. Performance Metrics

Mathematical analysis of the loss probability is a challenging task due to the multiple interactions between received signals at the BS [11]. Moreover, it also depends on the random number of users M. Due to this, we adopt the so-called *loss rate* $\mathcal{L}_R$ to evaluate the performance of the proposed MRC-SIC scheme, which is a weighted outage probability obtained through Monte Carlo simulations. It is defined as:

$$\mathcal{L}_{\mathcal{R}}(\lambda, D_u) = \sum_{k=1}^{M_{\max}} \Pr\left[\mathcal{O}_m^{\mathsf{sch}}\right] \Pr\left[M = k|\lambda\right], \quad (5)$$

where $\mathsf{sch} \in \{\text{MRC-DCM}, \text{MRC-SIC}\}$, whose outage probability can be numerically obtained with the aid of (3) and (4), respectively. In (5), $\Pr\left[M = k|\lambda\right]$ is the probability that the number of users equals k, which can be obtained using the Poisson probability density function from [20, Eq. (4-57)] as

$$\Pr\left[M = k|\lambda\right] = \frac{\lambda^k \mathrm{e}^{-\lambda}}{k!}. \quad (6)$$

Finally, the maximum number of users considered in the simulation is truncated to $M_{\max}$, by finding in (6) the maximum value of k whose probability of occurrence is not lower than a predefined threshold δ, *i.e.*

$$M_{\max} = \max\left\{k \,:\, \Pr\left[M{=}k|\lambda\right] > \delta\right\}. \quad (7)$$

IV. SIMULATION RESULTS

In this section we provide a few numerical examples comparing the proposed MRC-SIC scheme and the MRC-DCM scheme. The parameters adopted in this section are in Table I.

Fig. 4(a) presents the loss rate $\mathcal{L}_{\mathcal{R}}(\lambda, D_u)$ versus the arrival rate λ, for both the MRC-DCM and MRC-SIC schemes with $D_u \in \{2, 4, 6\}$. It can be seen that MRC-DCM is capable of supporting only very low arrival rates in the low-loss rate region. Also, increments in D_u generate an important increase in the slope of the $\mathcal{L}_{\mathcal{R}}$ curves. The lowest loss rates for $\lambda \geq 6$ is achieved by the lowest studied diversity, $D_u = 2$.

Noticeably, this effect is much less prominent in the MRC-SIC scheme. Instead, increases in D_u promoted better performance. This indicates that, for the adopted parameter set, the impact of collisions is much reduced when adopting SIC. However, it is expected that for higher λ values, the higher diversity schemes will eventually become less reliable due to overwhelming interference. This saturation effect is already visible in Fig. 4(a): the improvement in reliability in the $D_u = 4$ to $D_u = 6$ diversity increment is relatively smaller than the one observed for the $D_u = 2$ to $D_u = 4$ step.

Despite the improved performance, we have observed that the MRC-SIC receiver is very sensitive to the Γ parameter. In Fig. 4(b), where $\Gamma = 0$ dB and all other parameters are according to Table I, it is shown that the benefits of the SIC phase relatively worsen with decreases in the average transmission SNR, Γ. The impact of the decreased Γ is even more significant at high loads. Also, the saturation effect is more noticeable, given that, after the $D_u = 2$ to $D_u = 4$ diversity step, the reliability decreases with diversity increases.

V. CONCLUSIONS

This paper has studied the use of an MRC-SIC receiver in an uplink NOMA GF system. We have explored the impact of such design on the loss rate. It has been shown that the proposed scheme can achieve the expected reliability for URLLC applications. It also has become evident that the destructive collision assumption adopted often in order to simplify the issue of collisions is a very limiting consideration. The evaluated MRC-DCM showed a significantly lower reliability than the studied MRC-SIC scheme. And although both receiver models showed sensitivity to the effects of collisions, the MRC-DCM was particularly affected, with any increments in time domain diversity causing a reduction in performance, even at a low number of connecting devices.

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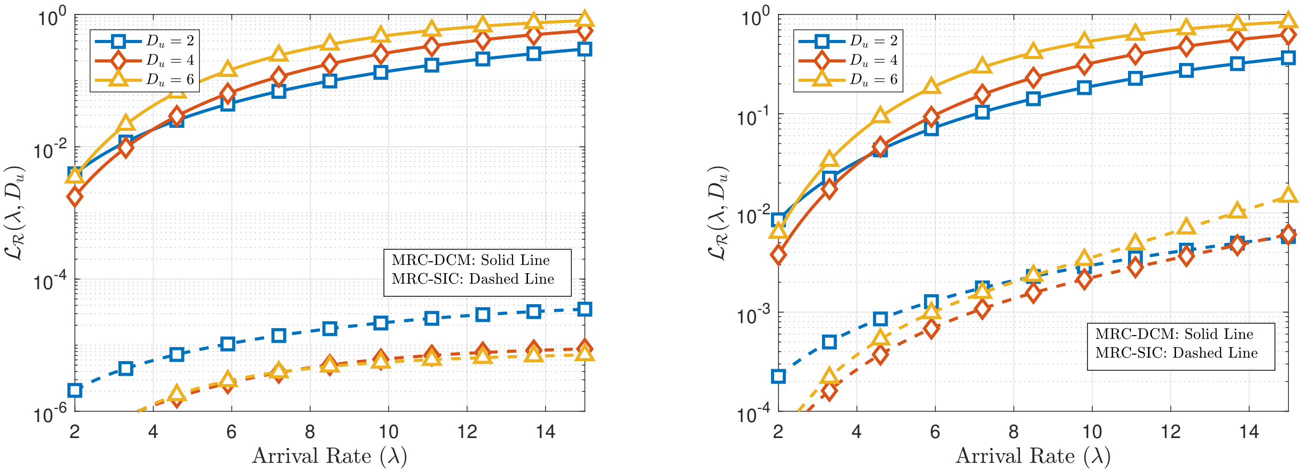

(a) $\Gamma = 9$ dB

(b) $\Gamma = 0$ dB

Fig. 4. Loss rate $\mathcal{L}_r$ versus the arrival rate λ for both MRC-DCM (solid line) and MRC-SIC (dashed line) schemes, when considering $D_u = \{2, 4, 6\}$ and (a) $\Gamma = 9$ dB; (b) $\Gamma = 0$ dB.

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