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Uplink Transmissions in URLLC Systems with Shared Diversity Resources

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***Abstract*—5G features flagship use cases with Ultra Reliable Low Latency Communication (URLLC), supported through high diversity. When multiple URLLC connections are only intermittently active, dedicating many diversity resources to a single connection leads to inefficient operation. We address this problem through shared diversity resources and compare it to per-link dedicated diversity. Two receiver types are considered, MMSE (minimum mean squared error) and MMSE-SIC (successive interference cancellation). Outage probability is evaluated by assuming channel estimation errors. The results show that it is possible to remain close to the reliability of reference system with a relatively low amount of pre-allocated resources.**

Keywords*—*URLLC, resource allocation and interference management, HARQ, transmit diversity, resource sharing.

I. INTRODUCTION

The advent of 5G opens up new possibilities and gives rise to a new category of use cases termed ultra reliable low latency communications (URLLC) [1]. Such services are characterized by very stringent requirements of e.g. 1 ms end-to-end latency and 99.999% reliability [2], which will be very challenging to accomplish using just the technologies and protocols of 4G and legacy systems [3].

High reliability requires use of some form of diversity. The way in which legacy systems achieve it is through hybrid automatic repeat request (HARQ), which involves exchange of feedback messages (ACK/NACK) that can trigger necessary retransmissions. However, such approach introduces latency that may not be affordable in many use cases. Another source of latency is connected to the scheduling request and grant procedure that needs to be performed before any transmission in the uplink can happen. Consequently, for extremely demanding applications some preallocation of the resources resembling that of semi-persistent scheduling [4] will be necessary in order to simultaneously cope with the reliability and latency requirements. However, such preallocation cannot be based on naïve assignment of dedicated resources to each user, as it could easily exhaust the available bandwidth and entails very poor system utilization when users are active only sporadically.

In this paper we provide an analysis of different uplink transmission schemes, taking as a baseline the traditional one used in LTE where each transmission and subsequent retransmissions are assigned dedicated resources. We compare it to a novel instance of hybrid schemes, which we coin *transmissions with shared diversity resources* (TSDR), and show that they offer significant savings of resources (which translate to lower latencies) while not compromising the performance. Inspired by the modeling of MIMO transmission [5], we propose an original, semianalytic evaluation framework which accommodates all the schemes of interest and allows us to numerically evaluate their performance in terms of outage probability. The framework allows for evaluation of the schemes assuming different conventional receivers, such as MMSE and MMSE with SIC, and takes into account impairments caused by realistic effect of non-ideal channel estimation [6][7].

Throughout the paper the following notation is used: $\circ$ to denote Hadamard (entry-wise) product, boldface uppercase and lowercase letters to denote matrices and vectors respectively, $(\cdot)^\dagger$ to denote Moore-Penrose pseudoinverse, $(\cdot)^{\mathrm{H}}$ to denote conjugate transpose, $(\cdot)_{i,j}$ to denote the $(i,j)^{th}$ entry of the matrix, $\mathbf{I}_N$ to denote identity matrix of size $N \times N$.

II. SYSTEM MODEL

We analyze a system consisting of a single cell serving N URLLC-type users transmitting in the uplink. At their disposal are periodic frames composed of M preallocated slots each consisting of K channel uses. The channel is modeled as Rayleigh fading and constant over all K uses of the slot. Each user is assumed to be active in a frame with only a certain probability p_i. When active, user i will transmit $k_i + 1$ replicas of the packet on a subset of available slots. Although we assume that each user has the same packet length equal to 1 slot, it can be easily generalized as long as the slot is kept as the smallest schedulable unit of transmission (no partial utilization). A toy example with a specific resource allocation is presented in Fig. 1. It is further assumed that the duration of the frame is adjusted to the deadline i.e. transmission which is successful by the end of the frame is guaranteed to fulfill the latency constraint and dropped otherwise. The channel output can be written as:

$$\mathbf{Y} = \mathbf{H}\mathbf{X} + \mathbf{N} \tag{1}$$

where $\mathbf{Y} \in \mathbb{C}^{M\times K}$ is a received signal, $\mathbf{X} \in \mathbb{C}^{N\times K}$ with its i^{th} row containing the i^{th} user's complex modulated symbols and $E\left[|x_{i,j}|^2\right] = P_x$, $\mathbf{H} \in \mathbb{C}^{M\times N}$ with $H_{i,j}$ denoting the channel gain of the j^{th} user in the i^{th} slot, and $\mathbf{N} \in \mathbb{C}^{M\times K}$ is an additive white Gaussian noise with zero mean and variance σ^2. The channel matrix $\mathbf{H}$ can be written as:

$$\mathbf{H} = \mathbf{G} \circ (\mathbf{S}\mathbf{P}) \tag{2}$$

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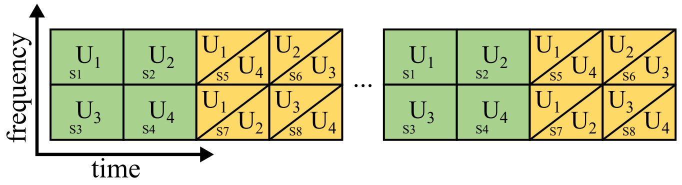

Fig. 1. Example of resource allocation for $N = 4$ users over $M = 8$ slots. User U_i performs $k_i = 2$ shared transmissions, $i = 1, \ldots, 4$. Green color denotes dedicated slots and yellow shared ones.

where $\mathbf{G}$ models the underlying uncorrelated Rayleigh flat fading channel, i.e. its entries are independent and identically distributed (i.i.d) zero mean circularly symmetric complex Gaussian (ZMCSCG) variables with unit variance, $\mathbf{S} \in \{0,1\}^{M \times N}$ is a 'mask' that corresponds to the access pattern of the scheduling scheme, i.e $S_{i,j}$ is 1 when the j^{th} user transmits in the i^{th} slot and $\mathbf{P} = diag\left((k_1+1)^{-1/2}, \ldots, (k_N+1)^{-1/2}\right)$ is a normalization matrix ensuring that the total transmitted power per user is independent of the number of transmissions.

A. Transmission schemes

The authors of this contribution postulate the use of *transmission with shared diversity resources*, that involves splitting the M resources into dedicated and shared portions. This way each user is guaranteed at least one uninterfered transmission and a configurable number of secondary transmissions in the shared part. An example of TSDR is presented in Fig. 1 and the corresponding matrix is:

$$\mathbf{S} = \begin{pmatrix} \mathbf{I}_4 \\ \mathbf{S}_{sch} \end{pmatrix}, \quad \mathbf{S}_{sch} = \begin{pmatrix} 1 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \end{pmatrix} \tag{3}$$

To benchmark the performance of TSDR we consider three other schemes:

1) Fully dedicated: As a baseline we consider a simple scheme where every transmission is assigned a distinct slot ensuring no mutual interference. This corresponds to the matrix $\mathbf{S}$ having $M = N + \sum_{i=1}^{N} k_i$ rows with a Hamming weight of 1 each. Obviously this is the most robust scheme but requires the highest number of resources for fixed k_i's.

2) Fully shared: On the other side of the spectrum is a fully shared scenario where each user is instructed to transmit its data on all of the available resources. This corresponds to the matrix $\mathbf{S}$ consisting of only 1's. Such a scheme requires the least resources for fixed k_i's.

3) Random: In this scheme user equipments (UEs) select a new subset of slots for transmission at random in each frame which entails different realizations of matrix $\mathbf{S}$. Such a scheme gives maximum flexibility to the users but the activity detection and data decoding is more challenging for the receiver which is forced to perform it blindly, as it doesn't know $\mathbf{S}$ in advance.

In all of the schemes, we assume that some initial random access procedure with parameter configuration has been already performed for each user (including k_i, M, pilot assignment and, for all non-random, also $\mathbf{S}$). Such step is necessary only once at the beginning (registering of the device) and stay valid until the resources are no longer needed by the UE and can be released.

III. PERFORMANCE ANALYSIS METHODOLOGY

For the purpose of analysis, we can look at the model and presented schemes from the point of view of MIMO system, where each User Equipment (UE) corresponds to a single transmit antenna, and each time-frequency slot is served by a different virtual receive antenna. Due to this structural similarity we are able to analyze their performance using results originally derived for MIMO.

In our evaluations we consider two types of receivers: MMSE offering a relatively good performance at a reasonable complexity, and a MMSE-SIC which is an iterative receiver achieving better results at the cost of an increased complexity.

To estimate the received signal of the form (1), receiver applies MMSE detection matrix $\mathbf{F}$ given by [5]:

$$\mathbf{F} = \left(\mathbf{H}^{\mathrm{H}}\mathbf{C}_n^{-1}\mathbf{H} + \frac{1}{P_x}\mathbf{I}_N\right)^{-1} \mathbf{H}^{\mathrm{H}}\mathbf{C}_n^{-1} \tag{4}$$

where $\mathbf{C}_n$ is the covariance matrix of the noise. The resulting estimate is the original signal contaminated by noise and interference from other users:

$$\widehat{\mathbf{X}} = \mathbf{FY} = \mathbf{FHX} + \mathbf{FN} \tag{5}$$

We include in our analysis the effects of imperfect channel estimation, which are expected to be relevant when resources are shared by multiple users. Following [8] we consider that N out of K symbols in each slot are used to transmit the training sequences which constitute rows of an $N \times N$ matrix $\mathbf{X}_{tr}$. The sequences of all N users are orthogonal and have a total power P_p i.e. $\mathbf{X}_{tr}\mathbf{X}_{tr}^{\mathrm{H}} = P_p\mathbf{I}_N$. The channel estimate $\widehat{\mathbf{H}}$ is obtained by applying a simple Maximum Likelihood (ML) estimator to the received training signal:

$$\widehat{\mathbf{H}} = \mathbf{Y}_{tr}\mathbf{X}_{tr}^{\dagger} = (\mathbf{HX}_{tr} + \mathbf{N})\mathbf{X}_{tr}^{\dagger} = \mathbf{H} + \underbrace{\frac{1}{P_p}\mathbf{NX}_{tr}^{\mathrm{H}}}_{\boldsymbol{\Delta}\mathbf{H}} \tag{6}$$

where each entry of the error matrix $\boldsymbol{\Delta}\mathbf{H}$ is i.i.d complex normal variable with variance $\sigma_H^2 = \frac{\sigma^2}{P_p}$. Consequently, the noisy channel estimate $\widehat{\mathbf{H}}$ introduces the distortion $\boldsymbol{\Delta}\mathbf{F}$ to the detection matrix such that the estimate of $\mathbf{X}$ becomes:

$$\widehat{\mathbf{X}} \cong (\mathbf{F} + \boldsymbol{\Delta}\mathbf{F})(\mathbf{HX} + \mathbf{N}) = \mathbf{FHX} + \widehat{\mathbf{N}} \tag{7}$$

The post-processing SINR (PPSINR) of each stream that can be derived from (7) takes the form:

$$\mathrm{SINR}(i) = \frac{P_x K \left|(\mathbf{FH})_{i,i}\right|^2}{P_x K \sum\limits_{j \neq i} \left|(\mathbf{FH})_{i,j}\right|^2 + (E[\widehat{\mathbf{N}}\widehat{\mathbf{N}}^{\mathrm{H}}])_{i,i}} \tag{8}$$

The PPSINR for MMSE-SIC receiver is obtained using the same formula (8) but the procedure is iterative with optimal ordering [9], i.e. at the end of each iteration stream with the highest PPSINR i_{max} is removed from $\mathbf{Y}$ by subtracting

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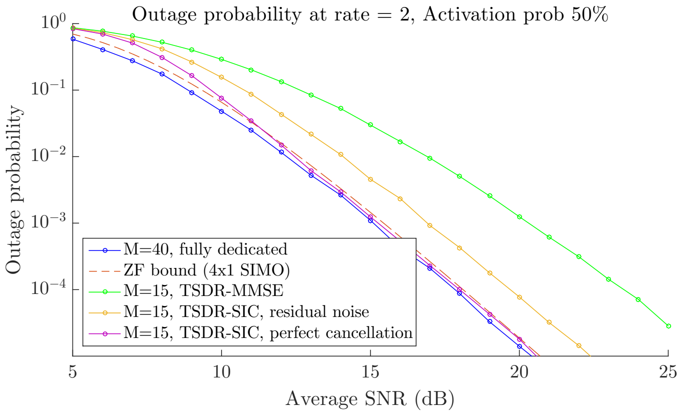

Fig. 2. Performance of fully dedicated scheme and TSDR scheme with different receiver complexity for $N = 10$ and $k_i = 3$

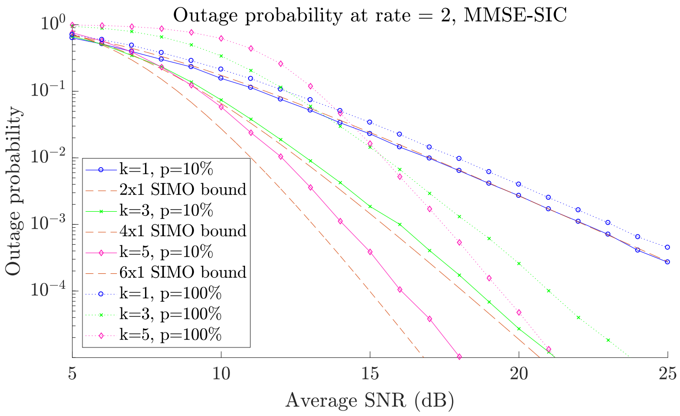

Fig. 3. Performance of TSDR schemes with variable number of secondary transmissions and fixed $M = 15$ and $N = 10$.

$\widehat{\mathbf{h}}_{i_{max}} x_{i_{max}}$. The decoding process is then repeated with fewer interfering streams (corresponding column of $\widehat{\mathbf{H}}$ removed) and slightly increased noise due to the residual term $\mathbf{\Delta h}_{i_{max}} x_{i_{max}}$.

For low values of p_i the chance that at most one UE is active is relatively high leading to a simple SIMO system. Following [7] we can approximate this case by:

$$\mathrm{SINR}_{\mathrm{SIMO}}(i) \sim \frac{P_x}{\sigma^2 + \sigma_H^2 P_x} \chi^2_{2(k_i+1)} \tag{9}$$

where χ^2_l is a chi-squared distributed random variable with l degrees of freedom.

Using the capacity formula for AWGN channel with i.i.d. ZMCSCG input signal process, the achievable rate is upper bounded by $\mathcal{R}_{max} = \log_2(1 + \mathrm{SINR}(i))$. Since for URLLC we are very often interested in outage measures of the system rather than pure throughput, the performance metric we will be using in the following section is the outage probability:

$$p_{out}(i) = Pr\left\{R > \mathcal{R}_{max}\left[\mathrm{SINR}(i)\right]\right\} \tag{10}$$

i.e. the probability that the rate R (in bits/s/Hz) at which UE transmitted its data was higher than the instantaneous maximum achievable rate.

Finally, we remark that explicit analysis of the latency is not the goal of this paper. Instead, we focus on analyzing how many slots M are necessary and how to best utilize them with respect to certain reliability targets. Taking into account other factors such as receiver processing delay, slot duration (determined by the subcarrier spacing and number of constituting OFDM symbols) allows to arrange the slots on a time-frequency grid so that a particular latency target is met.

IV. RESULTS

In this section, we present and discuss the results obtained through extensive simulations based on the analysis outlined in previous sections. The channel realizations $\mathbf{H}$ are generated as ZMCSCG according to (2) and with appropriate masks dependent on the scheme. The symbol power for each user is fixed to $P_x = 1$ while σ^2 is varied accordingly to SNR. For the purpose of calculating σ_H^2 the pilot power is set to $P_p = 4P_x$ so that the quality of channel estimation also depends on SNR. In the outage probability investigations, we select a relatively low transmission rate of 2 bits/s/Hz, which captures the robustness and low payload sizes of considered URLLC use cases.

In Fig. 2 we show the gains of using advanced SIC receivers in combination with schemes based on shared diversity resources. As a baseline we consider the performance of fully dedicated scheme and compare it with TSDR operating over reduced number of slots M and the same total number of transmissions per user k_i. We can see that with no SIC, which corresponds to the plain MMSE receiver, the performance is visibly degraded. However, using a more advanced receiver allows to approach the performance of dedicated scheme with almost three times less resources at a cost of moderate increase in complexity. To highlight the significance of imperfect channel estimation we provide the curves for both ideal SIC and the one introducing residual interference. In the rest of our evaluations we consider only the non-ideal one as it is more interesting to analyze and more realistic[1], while still significantly outperforming the MMSE receiver.

In Fig. 3 we analyze the interplay between the channel estimation errors, number of shared transmissions k_i and user activation probability. As shown by our analysis, channel estimation errors limit the interference cancellation capabilities of the receiver. In fact, one of the most important findings of this contribution is that, due to those imperfections, increasing k_i offers diminishing returns in terms of diversity and causes larger dependency on activation probability. Consequently, TSDR with higher degree of resource sharing (higher k_i) will observe more severe performance drop with increased p_i, which might be of importance if the traffic is bursty rather than uniform. For the outage probabilities of interest this degradation can be quite significant (e.g., 3dB of SNR for $k_i = 5$ and 2dB for $k_i = 3$ at 10^{-5} outage probability).

Fig. 4 compares TSDR and the idealized random scheme

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[1] In practice, the gap could be reduced in several ways. Simplest method involves increasing the number of shared slots while keeping k_i fixed to reduce the amount of interference. Another solution is to dedicate more resources to the pilots. Lastly, one could invest more computational power and use the successfully decoded stream as new pilots to refine the channel estimate.

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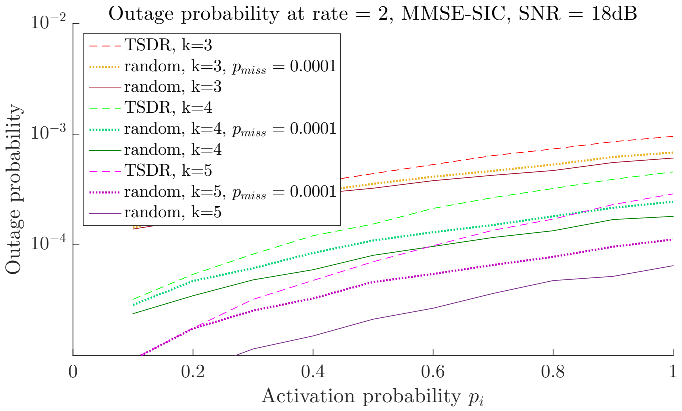

Fig. 4. Impact of the users' activation probability on the performance of TSDR and random schemes with fixed SNR = 18dB and $N = 10$.

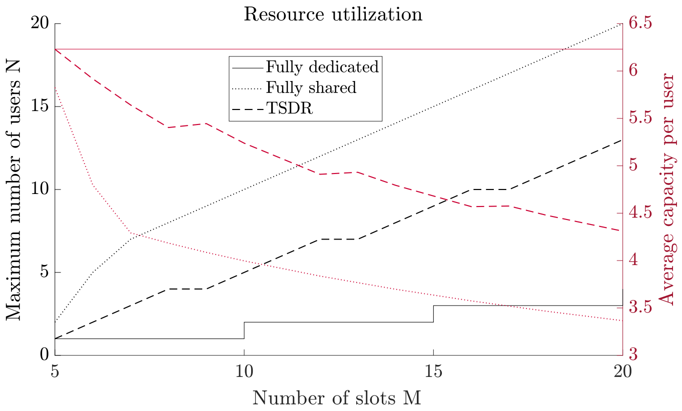

Fig. 5. Maximum number of users N that achieve the outage probability target of 10^{-5} at 20dB SNR and their average capacity.

described in section II-A in terms of their dependency on users' activation probability. We can see that for higher values of k_i randomization has an advantage since it allows to avoid too congested slots. However, we note that practical realizations of such random schemes will require the base station to perform blind activity detection and decoding which inevitably will lead to false positives and false negatives. To give some insight, we consider also a simplified model where each packet replica has a probability of miss-detection p_{miss} in which case the corresponding entry $\widehat{\mathrm{H}}_{i,j}$ is erroneously set to 0 and consequently $\Delta\mathrm{H}_{i,j} = -\mathrm{H}_{i,j}$. As shown in Fig. 4 the impact on performance is significant even for low values of p_{miss}. Another issue connected with random access arises when the number of available pilots is limited which causes sporadic collisions and pilot contamination between users. TSDR and other coordinated schemes offer a way to avoid that.

Lastly, in Fig. 5 we present our findings regarding the maximum number of supported users N fulfilling the outage probability target of 10^{-5} at 20dB SNR as a function of available resources M. To meet the requirements with fully dedicated scheme each user must transmit in total $k_i + 1 = 5$ replicas of the packet, which entails very poor scaling of the system where $N = \lfloor M/5 \rfloor$. When using TSDR the behavior of maximum N is much more linear as for every four slots invested it allows to add approximately three new users (over the simulated range the exact relationship is $N = 1 + \lceil 3(M-5)/4 \rceil$). For the fully shared scheme, the number of users N is linear with M thus achieving an upper bound (we do not consider here the underdetermined systems where $N > M$). However this scheme requires that $k_i+1 = M$ which quickly becomes computationally prohibitive. On the same figure we also provide the achievable average capacity per user as dictated by their PPSINR. We can see that TSDR significantly outperforms the fully shared scheme in that metric. The results can be interpreted as follows: more replicas lead to lower mean and variance of the PPSINR (making the curves in Fig. 3 steeper and shifted to the right). This could be dangerous if the SNR cannot be reliably estimated due to, for example, large fluctuations of the inter-cell interference.

V. CONCLUSION

In this publication we propose a novel uplink transmission scheme, TSDR, in which resources are shared by users in a coordinated manner. The scheme relies on the usage of advanced (SIC) receiver processing in order to achieve the URLLC requirements. We show that TSDR offers very large saving of resources compared to schemes in which users have dedicated resources for transmission. At the same time, it strikes a balance between excessive complexity imposed by random schemes and computational burden of fully shared scheme. Furthermore, our analysis reveals the importance of accounting for channel estimation errors in the design of the air interface, especially when advanced receivers are considered.

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