Reconfigurable Intelligent Surface-Aided Grant-Free Access for Uplink URLLC

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***Abstract*—Reconfigurable intelligent surfaces (RISs) have been recently considered as one of the emerging technologies for future communication systems by leveraging the tuning capabilities of their reflecting elements. In this paper, we investigate the potential of an RIS-based architecture for uplink sensor data transmission in an ultra-reliable low-latency communication (URLLC) context. In particular, we propose an RIS-aided grant-free access scheme for an industrial control scenario, aiming to exploit diversity and achieve improved reliability performance. We consider two different resource allocation schemes for the uplink transmissions, i.e., dedicated and shared slot assignment, and three different receiver types, namely the zero-forcing, the minimum mean squared error (MMSE), and the MMSE-successive interference cancellation receivers. Our extensive numerical evaluation in terms of outage probability demonstrates the gains of our approach in terms of reliability, resource efficiency, and capacity and for different configurations of the RIS properties. An RIS-aided grant-free access scheme combined with advanced receivers is shown to be a well-suited option for uplink URLLC.**

***Index Terms*—Reconfigurable intelligent surface, grant-free, URLLC, resource allocation.**

I. Introduction

The fifth generation (5G) wireless systems aim to efficiently support three key generic services with broadly diverging operational requirements, i.e., enhanced mobile broadband (eMBB), massive machine-type communication (mMTC), and ultra-reliable low-latency communication (URLLC) [1]–[4]. In particular, eMBB services are associated with high data rate requirements with moderate reliability demands [5]; mMTC typically involves a massive number of sporadically active devices transmitting delay-tolerant traffic in small data payloads [6]; and URLLC entails low-latency transmissions of small payloads with very high reliability requirements often imposed by mission-critical application scenarios [7].

In the particular case of the URLLC service category, a wide range of emerging use cases are expected to be supported. Example application scenarios include wireless control and automation in industrial factory environments, power system protection, inter-vehicular communications for improved traffic safety and efficiency, remote health services and the tactile Internet. All these use cases require extremely low latency values (i.e., user-plane radio latency 1ms) and, simultaneously, an outage probability of less than 10^{-5} (i.e., reliability higher than 0.99999) in terms of block error rate (BLER) [5]. These stringent URLLC requirements challenge the classical design principles of cellular networks and call for radical radio access network (RAN) technical enablers.

Among the various technical enablers proposed for URLLC enhancement, e.g., flexible numerology, mini-slot frame structure, link adaptation, etc., grant-free access protocols aim to minimize the latency associated with the uplink connection establishment. In grant-free multiple access, the signaling overhead can be significantly reduced by allowing user equipment (UE)s to directly transmit their uplink data without sending scheduling requests to the base station (BS) and waiting for uplink grant allocation. However, the low protocol overhead comes at the cost of increased collisions among the contending UEs, which may compromise the required reliability levels.

Consequently, numerous variants of grant-free access protocols have been developed over the recent years. Solutions based on central coordination and feedback capabilities are rendered insufficient for mission-critical applications, especially at high-frequency bands and in harsh propagation environments where shadowing/blockage can cause direct links to the BS to be in outage. An interesting approach relies on the *a priori* allocation of the radio resources for each UE transmission and subsequent retransmissions. In [8], the authors propose a resource-efficient transmission scheme where resources are shared among UEs in a coordinated manner. Their approach improves reliability while relying on sophisticated receiver types, such as minimum mean squared error (MMSE)-successive interference cancellation (SIC).

In this paper, we leverage the emerging paradigm of reconfigurable intelligent surface (RIS) to enhance the performance of grant-free access. An RIS consists of a number of programmable nearly passive elements with ultra-low power consumption, each of which can be properly tuned to apply arbitrary phase shifts to the impinging radio signals [9]. The potential of RISs has recently attracted extensive research attention and their applicability has been explored in various network scenarios, such as energy-efficient beamforming, physical-layer security, wireless power transfer, indoor positioning [10]–[12]. Based on their unique capability of controlling the wireless propagation environment [13]–[15], RISs constitute a promising and low-cost solution to provide link diversity and achieve ultra-reliable uplink connectivity.

In this context, we propose an RIS-aided grant-free access scheme tailored for mission-critical URLLC applications. In particular, we consider an RIS-based network architecture for uplink data transmissions, aiming to exploit the additional degree of freedom for system optimization. Based on the benchmark framework followed in [8], we consider two different uplink resource allocation schemes, i.e., dedicated and shared, for the UE transmissions and we evaluate the performance in terms of outage probability for different receiver types. Our numerical simulations reveal the reliability and capacity gains of the RIS-aided grant-free access compared to the performance of the legacy grant-free access method. Besides allowing for reduced receiver complexity, our proposed scheme improves the resource utilization as it requires less number of slots for UE retransmissions. Finally, in an effort to demonstrate the RIS capability in controlling the radio environment, we quantify the impact of the main RIS features, i.e., number of elements and phase shifting values, in the overall performance.

Organization: The rest of this paper is organized as follows. We present the system model in Section II. In Section III, we provide the characteristics of the considered receiver types and we define the outage probability, which constitutes the key performance metric of our analysis. In Section IV, we present and discuss the numerical results obtained through extensive simulations. Finally, concluding remarks and future research directions are drawn in Section V.

Notation: The notation used in this paper is the following: $(\cdot)^H$ denotes the conjugate transpose, $(\cdot)_{i,j}$ represents the $(i,j)^{th}$ entry of a matrix, the uppercase and lowercase boldface letters denote matrices and vectors respectively, while $\mathbf{I}_\mathrm{N}$ represents an $N \times N$ identity matrix.

II. System Model

In this section, we present the signal model for the uplink grant-free transmission assisted by an RIS.

As illustrated in Fig. 1, we consider a wireless industrial control scenario where a single BS is serving N URLLC-type sensors attached to a motor to support a control-loop. The sensors transmit their mission-critical data related to the motor states in periodic uplink frames composed of M slots, each of which consists of L channel uses. Without loss of generality, it is assumed that the packet length of each sensor occupies 1 slot. We further consider a Rayleigh fading model for the channel, which remains constant over all L uses of the slot. The received signal, $\mathbf{Y} \in \mathbb{C}^{M\times L}$, at the BS can be written as

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

where $\mathbf{X} \in \mathbb{C}^{N\times L}$ contains the complex modulated symbols of the sensors with transmit power $E[|x_{i,j}|^2] = P_x$; $\mathbf{H} \in \mathbb{C}^{M\times N}$ contains the channel gains of the sensors in the available slots;

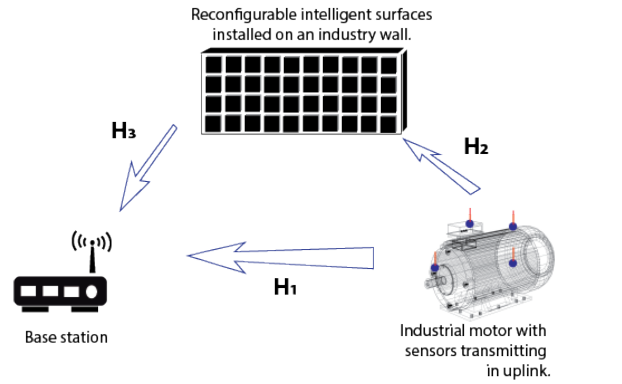

Fig. 1. System model of an RIS-aided uplink sensor data transmission in a wireless industrial environment. The RIS is deployed on a nearby wall in the vicinity of both communication ends.

and $\mathbf{N} \in \mathbb{C}^{M\times L}$ is an additive white Gaussian noise with zero mean and variance σ^2. We further assume that the total transmitted power per sensor is independent of the number of transmissions.

Besides the direct signal path between the sensors and the BS, communication also takes place via the RIS which consists of K passive reflecting elements deployed in the vicinity of both communication ends. Thus, $\mathbf{H}$ can be decomposed as

$$\mathbf{H} = \mathbf{H}_1 + \mathbf{H}_3\mathbf{\Phi}\mathbf{H}_2, \tag{2}$$

where $\mathbf{H}_1 \in \mathbb{C}^{M\times N}$ represents the direct channel between the sensors and the BS; $\mathbf{H}_3 \in \mathbb{C}^{M\times K}$ corresponds to the channel between the RIS and the BS; $\mathbf{\Phi} \triangleq \mathrm{diag}[\phi_1, \phi_2, \ldots, \phi_K]$ is a diagonal matrix accounting for the effective phase shifting values ϕ_k, $\forall k = 1, 2, \ldots, K$, applied by all RIS reflecting elements; and $\mathbf{H}_2 \in \mathbb{C}^{K\times N}$ represents the channel between the sensors and the RIS. The entries of $\mathbf{H}_1, \mathbf{H}_2, \mathbf{H}_3$ are also modeled as independent and identically distributed (i.i.d.) zero mean circularly symmetric complex Gaussian (ZMCSCG) variables. The effective phase shifting value for the k-th element of the RIS is defined as

$$\phi_k \in \mathcal{F} \triangleq \left\{ e^{\frac{j2\pi m}{2^b}} \right\}_{m=0}^{2^b-1}, \tag{3}$$

where $\mathcal{F}$ is the set with the available phase shifting values; $j \triangleq \sqrt{-1}$ is the imaginary unit; m represents the phase shifting index; and b is the phase resolution in number of bits [16]. The number of phase shifting values per RIS element is 2^b.

Two different resource allocation schemes for the uplink grant-free transmissions of the sensors[1] are considered at the BS. In particular,

1) A *dedicated* resource allocation scheme, where every sensor transmission is assigned a distinct slot. This scheme constitutes a robust approach against mutual interference by allocating orthogonal resources to the

[1] Similar to [8], we assume that an initial uplink parameter configuration has been already performed during the network registration of the sensors. This can be carried out as part of the system information broadcasted by the BS over the cell.

sensors. However, despite the controlled interference environment, this scheme may prove inefficient in terms of resource utilization.

2) A *shared* resource allocation scheme, where all sensors are able to share the available slots among them. In stark contrast to the dedicated assignment, this scheme is more spectrum-efficient at the expense of induced intra-slot interference in the sensors' transmissions.

III. Performance Analysis

Based on the system model defined in Section II, we consider a generic RIS-based multiple-input multiple-output (MIMO) framework for the purpose of the analysis, where each sensor corresponds to a single transmit antenna, and each time-frequency slot is served by a different virtual receive antenna [8]. This approach allows us to assess the performance using standard tools originally derived for a MIMO system analysis.

The estimation of the original transmitted signal is contaminated by the inter-stream interference from the other sensors and the noise. Assuming perfect channel estimation, the detected signal can be expressed as

$$\hat{\mathbf{X}} = \mathbf{FY} = \mathbf{FHX} + \mathbf{FN}, \tag{4}$$

where $\mathbf{F}$ depends on the receiver design. In what follows, we consider three different types of MIMO receivers, i.e., zero-forcing (ZF), MMSE, and MMSE-SIC, for the recovery of the transmitted symbols of the sensors [17]. In particular,

1) A ZF receiver which focuses on completely eliminating the intersymbol interference (ISI) with no control over the energy in the stream of interest. In particular, it aims to minimize the mean squared estimation error (averaged over the noise) on the symbols under the constraint of complete elimination of ISI. To estimate the received signal of the form defined in (1), the receiver applies the following ZF detection matrix $\mathbf{F}_{\text{zf}}$ given by

$$\mathbf{F}_{\text{zf}} = \mathbf{H}\ (\mathbf{H}^H\mathbf{H})^{-1}\mathbf{H}^H. \tag{5}$$

2) An MMSE receiver which aims to minimize the average estimation error on the transmitted symbols and the average is taken over the transmitted symbols and the noise. Different from the ZF receiver, the MMSE does not require complete ISI elimination. The equivalent expression of the MMSE receiver, $\mathbf{F}_{\text{mmse}}$, used to estimate the received signal is given by

$$\mathbf{F}_{\text{mmse}} = \left(\mathbf{H}^H\mathbf{H} + \frac{\sigma^2}{P_x}\mathbf{I}\right)^{-1}\mathbf{H}^H. \tag{6}$$

3) An MMSE-SIC receiver which relies on an iterative principle where, at each iteration, a data stream is decoded considering the other streams as interference. The decoded stream is then removed from the list of interfering streams and, at the next iteration, the selected stream is decoded with one less interferer. The detection matrix for the MMSE-SIC receiver has the same expression as in (6). However, the procedure to calculate the post-processing SINR (PPSINR) is iterative with optimal ordering. An MMSE-SIC receiver design improves the detection accuracy at the cost of increased computational complexity compared to the previous receivers.

Based on Eq. (4), the PPSINR of a sensor data stream i can be expressed as

$$\text{SINR}(i) = \frac{P_x L|(\mathbf{FH})_{i,i}|^2}{P_x L\sum_{j\neq i}|(\mathbf{FH})_{i,j}|^2 + (E[\mathbf{NN}^H])_{i,i}}. \tag{7}$$

For the performance assessment of mission-critical URLLC scenarios, as the one considered in this paper, the outage probability per sensor data stream is chosen as the most appropriate reliability metric. In general, the outage probability constitutes a widely-used information theoretic tool to evaluate the performance in MIMO systems. For a selected transmission rate R, it is computed as

$$p_{\text{out}}(i) = Pr\{R > \mathcal{R}_{\max}(i)\}, \tag{8}$$

where $\mathcal{R}_{\max}(i) = \log_2(1 + \text{SINR}(i))$ corresponds to the maximal achievable rate for reliable communication of sensor data stream i. Using (8), the outage probability for each receiver design can be computed individually.

IV. Numerical Results

As described in Section III, we aim to assess the performance from the viewpoint of a MIMO framework. An RIS-aided i-sensor MIMO communication model is therefore considered, as illustrated in Fig. 1. The reliability performance of grant-free access is evaluated in terms of outage probability for different receiver types, i.e., ZF, MMSE, and MMSE-SIC, and uplink resource allocation schemes, i.e., dedicated and shared. The sensors are equipped with omni-directional antennas and transmit their data simultaneously. The RIS elements are deployed uniformly on an ideal rectangular surface and the effective phase shifting values defined in Eq. (3) are considered to have low phase resolution tuning capabilities, i.e., $b = 1$.

In order to obtain an averaged system performance, the achievable rates for each of the considered receiver types are averaged over $2 \cdot 10^5$ channel realizations drawn from an i.i.d. Rayleigh distribution. A sensor transmission rate $R = 2$ bits/s/Hz is also assumed for the outage probability calculations.

Fig. 2 illustrates the performance comparison of the different receiver types and resource allocation schemes for a grant-free transmission with/without the assistance of an RIS. We can observe that a grant-free scheme with shared slots and a ZF receiver leads to a degraded performance with respect to the grant-free scheme with dedicated slot assignment. However, as the receiver complexity increases, we note that the shared grant-free scheme gradually achieves superior performance compared to the dedicated case. In addition, this reliability gain is attained with relatively less (nearly half) slots, which reveals the resource efficiency of the shared approach. In both resource allocation methods, the reliability gains of an RIS-aided grant-free access can be easily identified for all receiver types. Interestingly, we can observe that an MMSE receiver

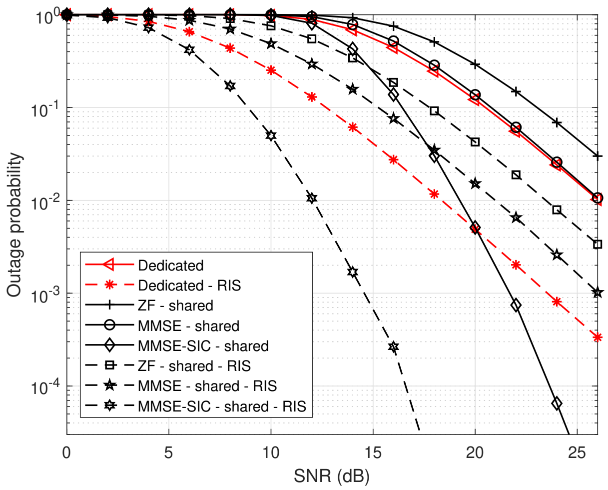

Fig. 2. Performance comparison of the different receivers and resource allocation schemes for a grant-free transmission of $N = 5$ sensors with/without the assistance of an RIS with $K = 6$ elements. A number of $M = 11$ slots is considered for the dedicated scheme whereas $M = 6$ for the shared one.

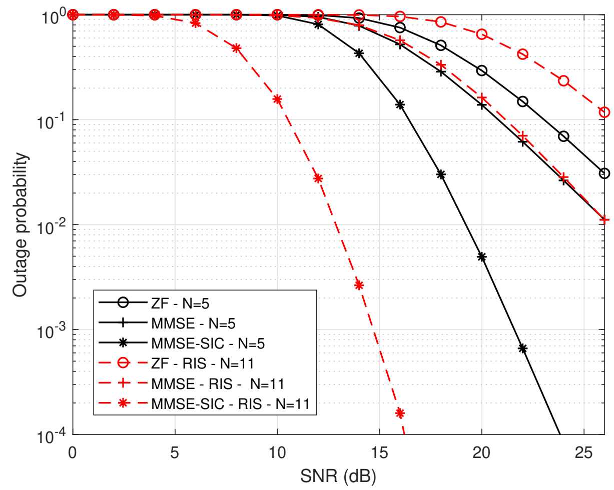

Fig. 3. Performance comparison of a non-RIS grant-free access scheme supporting $N = 5$ sensors and an RIS-aided grant-free access scheme supporting $N = 11$ sensors. A shared resource allocation strategy is considered and the number of RIS elements is $K = 6$.

in an RIS-aided system outperforms the sophisticated MMSE-SIC receiver in a system with no RIS for signal-to-noise ratio (SNR) values until 18dB. Thus, the presence of RIS may allow the use of receivers with lower computational complexity to achieve acceptable outage performance. Finally, we remark that the use of RIS in combination with advanced receiver designs can achieve significantly low outage probability values, revealing their potential in supporting URLLC.

Fig. 3 corroborates the capacity gains achieved with an RIS-aided grant-free access scheme. In particular, an MMSE receiver in an RIS-aided system supporting 11 sensors simultaneously transmitting their data, achieves nearly similar outage performance compared to an MMSE receiver in a non-RIS setup with 5 sensors. Thus, an RIS-aided grant-free scheme is able to support more than double of the number of sensors using the same amount of slots. The capacity potential of RIS is further enhanced when a higher-complexity receiver, i.e., MMSE-SIC, is considered.

Fig. 4 illustrates how the different retransmission strategies compare in terms of outage probability for a grant-free scenario of dedicated slot allocation with/without the assistance of an RIS. In particular, each of the $N = 2$ sensors is assigned a dedicated slot for its data transmission while two allocation cases are considered for their retransmissions: *i*) 4 dedicated slots per sensor; and *ii*) 1 dedicated slot per sensor. While for a non-RIS system, the first case (i.e., 4 slots/sensor) is more robust in the high SNR regime compared to the more conservative second case (i.e., 1 slot/sensor), we can observe that an RIS-aided system can significantly improve the performance even for a smaller amount of retransmission slots. It can be also noticed that the outage probability further decreases when the number of K elements of the RIS increases.

Finally, Table I shows the impact of the tuning capabilities

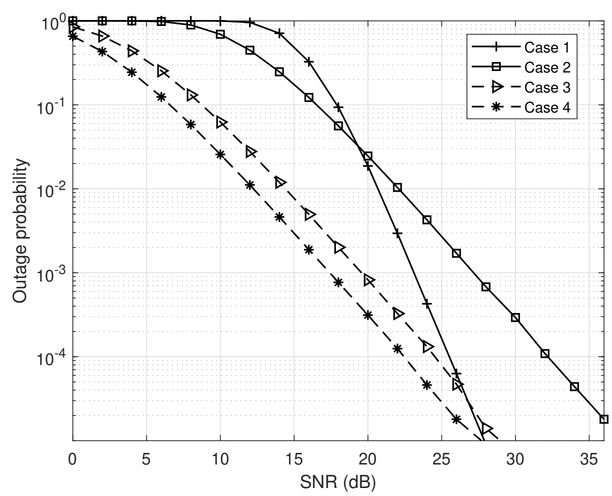

Fig. 4. Performance comparison of different retransmission policies for a dedicated resource allocation scenario with $N = 2$ sensors and $M = 10$ slots. The following cases are illustrated: Case 1: 4 retransmission slots per sensor with no-RIS assistance; Case 2: 1 retransmission slot per sensor with no-RIS assistance; Case 3: 1 retransmission slot per sensor with an RIS of $K = 6$ elements; Case 4: 1 retransmission slot per sensor with an RIS of $K = 8$ elements.

of the RIS elements on the outage probability performance for a grant-free scenario of shared resources with an MMSE-SIC receiver. In particular, we consider an RIS consisting of $K = 3$ elements with 1-bit phase resolution, i.e., $\phi_k = 1$ when $m = 0$, and $\phi_k = -1$ when $m = 1$, for $k = 1, 2, 3$. As it can be observed, for a simulation of $5 \cdot 10^6$ channel realizations, a proper configuration of the phase shifting values among the RIS elements affects the outage performance. These findings

TABLE I
PERFORMANCE COMPARISON OF THE DIFFERENT COMBINATIONS OF PHASE SHIFTING VALUES FOR 1-BIT PHASE RESOLUTION ($b = 1$), $R = 1.5$ BITS/S/HZ AND SNR = 24dB.

Combination	Element 1	Element 2	Element 3	Outage
1	1	1	1	$1.1 \cdot 10^{-5}$
2	1	1	-1	$0.96 \cdot 10^{-5}$
3	1	-1	1	$1.18 \cdot 10^{-5}$
4	1	-1	-1	$1.3 \cdot 10^{-5}$
5	-1	1	1	$1.04 \cdot 10^{-5}$
6	-1	1	-1	$0.9 \cdot 10^{-5}$
7	-1	-1	1	$1.0 \cdot 10^{-5}$
8	-1	-1	-1	$1.02 \cdot 10^{-5}$

corroborate the flexibility offered by an RIS-based architecture, even with low phase resolution reflecting elements, in URLLC scenarios with stringent outage requirements, e.g., in the order of 10^{-5}.

V. CONCLUSIONS

In this paper, we propose a novel grant-free access scheme assisted by an RIS architecture and tailored for uplink URLLC use cases. We consider two different resource allocation schemes for the uplink data transmissions, i.e., dedicated and shared slot assignment, and we evaluate the performance in terms of outage probability for linear receivers of different computational complexity. Our extensive simulation results showcased that an RIS-aided grant-free access scheme in combination with advanced SIC receivers substantially improves the reliability performance, even at the low SNR regime. In addition, we quantified the resource utilization and capacity gains offered by our proposed scheme. Finally, we showed the impact of the tuning capabilities of an RIS, i.e., different number of elements and phase shifting values, on the outage probability. The overall performance assessment revealed the suitability of an RIS-based framework for the support of mission-critical uplink URLLC scenarios associated with stringent requirements.

Future interesting lines of research include the consideration of energy efficiency aspects for the RIS-aided grant-free access as well as the joint design of the transmit sensor powers and the phase shifting values for the RIS elements. An extension of this work would involve the study of the impact of channel estimation and feedback overhead on the performance of the RIS-aided grant-free system. Other impairment to be evaluated in further studies is related to the delay path impact between sensors and base station and sensors and RIS elements, specially in the URLLC scenario.

ACKNOWLEDGEMENTS

This work is partly funded by Academy of Finland via ee-IoT project (ICT2023/n.319009), via FIREMAN consortium (CHIST-ERA/n.326270), and via EnergyNet (Research Fellow/n.321265&328869), and by the Spanish National Foundation (PCI2019-103780), and the Generalitat de Catalunya under Grant 2017 SGR 891.

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