ABSTRACT  
5G and beyond 5G (B5G) wireless systems promise to support services with different requirements in the same network, as enhanced mobile broadband (eMBB), ultra-reliable low-latency communications (URLLC), and massive machine type communication (mMTC). One alternative is to consider the network slicing paradigm, where the wireless network resources are shared (or sliced) among active services with different requirements. In addition, another emerging technology, that is considered as a key enabler for B5G wireless systems, is the intelligent reflecting surfaces (IRS). From the deployment of an IRS, it is possible to improve the received signal quality and consequently increase the overall network capacity. Therefore, in this paper, we investigate the use of IRS to support simultaneous eMBB and URLLC services. We evaluate the achievable rate of an IRS-aided radio access network, where the uplink resources are shared between eMBB and URLLC users either under heterogeneous orthogonal multiple access (H-OMA) or heterogeneous non-orthogonal multiple access (H-NOMA) techniques. Results show that exploiting an IRS can considerably increase the eMBB rate and the URLLC reliability simultaneously, regardless of whether operating under H-OMA or H-NOMA. Moreover, we also provide some insights on the best user pairing strategy, showing that higher rates are achieved by matching many eMBB users near to their IRS and relatively close to the base station.

INDEX TERMS 
Enhanced Mobile Broadband (eMBB), Intelligent Reflecting Surfaces (IRS), Network Slicing, Ultra-Reliable Low-Latency Communications (URLLC).

I. INTRODUCTION

Fifth-Generation (5G) and Beyond 5G (B5G) wireless communications systems will concurrently support many services based on three different types of use cases (as eMBB, URLLC, and mMTC) with heterogeneous requirements in the same operator network infrastructure, thus demanding a high degree of flexibility and scalability. One of the sectors that will be greatly impacted by the B5G networks development and that presents the need for supporting services with heterogeneous requirements in the same network infrastructure is the industry, as in the case of discrete manufacturing [1]. Manufacturing is diverse and heterogeneous and it is characterized by a large number of use cases, such as (i) Factory automation, which includes motion control, control-to-control, mobile robots, and massive wireless sensor networks. To support this use case, the B5G networks need to fulfill stringent requirements in terms of reliability, latency, communication service availability, and determinism [1], [2]; and (ii) Human-machine interfaces (HMI), which include many diverse devices for interaction between people and production systems [1], [2]. These can be panels mounted to a machine or production line, as well as standard IT devices, such as laptops, tablet PCs, smartphones, etc. In addition, augmented and virtual reality systems are expected to play an increasingly important role in the industry [2]. The above use cases impose stringent requirements. For example, very low latency, high reliability and high data rate are imperative for some of them. Therefore, eMBB or URLLC alone cannot meet the demands of these new applications, and therefore the network must be able to support heterogeneous services.

One alternative to accommodate the coexistence of such heterogeneous services in the same network is by means of...
the network slicing paradigm [3], [4], where one physical network is sliced into multiple virtual networks designed and optimized to support specific services (as eMBB, URLLC, mMTC) and their requirements. In addition, the network slicing paradigm allows the wireless resource sharing among active services with different requirements.

Notwithstanding the advantages of considering the network slicing paradigm, one of the main challenges in wireless communication systems is the non-deterministic nature of fading channels. In order to overcome this difficulty, a new technology has recently attracted great interest. Intelligent reflecting surfaces (IRS), or reconfigurable intelligent surfaces, are meta-surfaces comprising a large number of reflecting elements, capable of reflecting the incident signal with a given phase/amplitude shift [5]. By densely deploying IRSs in wireless communication networks and intelligently coordinating their elements, the wireless channels between the transmitter and receiver can be intentionally and deterministically controlled to improve the signal quality at the receiver and the network capacity [6]–[9].

Therefore, we foresee the potential of an IRS to control the wireless channel in a given setup as to favour the slicing of physical layer resources, and thus improving the performance of heterogeneous services as eMBB and URLLC, both in orthogonal and non-orthogonal multiple access. The IRS capability of controlling the wireless channel and the spectral efficiency of the physical layer network slicing paradigm seem a good fit for pushing even further the performance of 5G and B5G system in demanding scenarios as industrial automation.

A. RELATED WORKS

Recent works have investigated the network slicing between eMBB, URLLC and/or mMTC users in the scope of the radio access network (RAN) [10]–[13]. In the aforementioned works, the authors consider both heterogeneous orthogonal multiple access (H-OMA) and heterogeneous non-orthogonal multiple access (H-NOMA) strategies, where the term “heterogeneous” specifies the sharing of resources between users with different requirements (e.g. sharing between eMBB and URLLC users).

In [10], Popovski et al introduce a theoretic approach to investigate the trade-off between the orthogonal and non-orthogonal RAN slicing for eMBB and URLLC users, as well as for eMBB and mMTC users. Results show that, in general, H-NOMA can achieve higher rates than H-OMA. In [11], the H-OMA RAN resource slicing is studied considering eMBB and URLLC services in order to maximize the achievable rate of the eMBB users subject to the URLLC reliability requirement. In [12], the co-scheduling of eMBB and URLLC traffic and the maximization of the minimum rate at the eMBB users subject to the URLLC traffic requirements, considering H-OMA RAN slicing, are investigated. In [13], the authors elaborate on the model from [10] by considering a maximum-matching diversity (MMD) method [14] to allocate channels to the eMBB users, where the MMD-aided eMBB users share the network resources with a URLLC user. The use of MMD for frequency channel allocation can lead to significant gains independently of the multiple access technique adopted, H-OMA or H-NOMA. Later, [15] extends [13] by proposing a hybrid multiple access strategy that mixes H-OMA and H-NOMA techniques, achieving the benefits of both strategies.

In the previously cited works, the heterogeneous users directly communicate with a common base station (BS). However, in practical scenarios, the direct link between BS and users can be totally or partially blocked, reducing the capacity/reliability and possibly compromising the communication. In this situation, one could resort to an IRS [7], [18]. Due to its promising potential, some works have recently considered the use of an IRS in the scope of B5G [16], [17], in particular for aiding URLLC communications. In [16], the authors apply an IRS to assist the communication between multiple URLLC users and the BS, showing that the multi-user detection capability can be increased. In addition, the work in [17] considers an industrial control scenario, where multiple sensors communicate with a common BS with the aid of an IRS. By exploiting the diversity provided by IRS, it is shown in [17] that gains in terms of reliability and capacity can be achieved. In [16], [17] the authors assume that only URLLC services are supported in the network. However, in this paper, we consider heterogeneous users assisted concurrently in the same network by means of the network slicing paradigm. In addition, differently from [10]–[13], [15]–[17], we evaluate clustering approaches for pairing up URLLC and eMBB users, in order to maximize the performance of both multiple access strategies (H-OMA and H-NOMA). Table 1 summarizes the scope of the most related papers and highlights the differences with this work.

B. CONTRIBUTIONS

Although the clear promising potential of integrating the network slicing paradigm and the IRS technology, supporting heterogeneous devices in the same network usually brings some challenges. First, due to the stringent latency requirement, it is not practical to assume knowledge of the URLLC users channel state information (CSI) before transmission, as such estimation requires significant signaling exchange, which increases the latency and, consequently, can potentially violate the URLLC requirements. Therefore, the optimal design of phase shifts at the IRS from the URLLC perspective is not feasible. Second, RAN slicing usually considers H-OMA and/or H-NOMA, however, H-NOMA is considered interference limited due to the fact that multiple users share the same radio resources and, consequently, present strong co-channel interference [19], [20]. In order to mitigate this issue,
different works have proposed to group users in clusters based on their channel conditions [20], [21].

Motivated by the above challenges, in this paper, we investigate the influence of an IRS in the RAN slicing between URLLC and eMBB services, considering both H-OMA and H-NOMA strategies. In addition, we also discuss different clustering approaches and provide some insights on the best user clustering strategy for a heterogeneous scenario. In addition, as pointed out in Table 1 and to the best of the authors’ knowledge, this is the first paper that investigates the union of RAN slicing paradigm, IRS, and different multiple access strategies in order to simultaneously support and improve the achievable rate of heterogeneous services. Therefore, the main contributions of this work are summarized as follows:

- We demonstrate that using an IRS improves the performance of both eMBB and URLLC services, regardless the multiple access strategy (H-NOMA or H-OMA).
- We show that H-NOMA is the best strategy when the eMBB user is close to the BS and the IRS assists the URLLC user only. On the other hand, we show that in other scenarios H-OMA can outperform its non-orthogonal counterpart.
- We assess the influence in the achievable rate when the IRS is used to assist only a single service (eMBB or URLLC) or both services simultaneously. The best user clustering strategy is to match $F_b$ eMBB users near to the IRS with an URLLC user close to the BS.

The rest of this paper is organized as follows. Section II presents the system model and the evaluated scenarios. Section III describes the RAN slicing concept, presents the performance metric, and the types of beamforming design to be considered. Section IV presents numerical results and discussions. Finally, Section V concludes the paper.

**Notations:**Italic lower-case letters like $a$ denote variables, bold-faced upper case letters like $A$ denote matrices, while a bold-faced lower case letter $a$ represents a vector. In addition, $(\cdot)^H$ denotes the conjugate transpose, $\mod (\cdot)$ is the modulo operation, $\lfloor \cdot \rfloor$ denotes the absolute value, $\lceil \cdot \rceil$ is the norm execution, and $\lceil \cdot \rceil$ denotes the floor function. Moreover, Table 2 and Table 3 contain respectively the list of acronyms and symbols used in this paper.

### Table 2. List of Acronyms.

| Acronym   | Meaning                                         |
|-----------|-------------------------------------------------|
| 5G        | Fifth generation                                |
| B5G       | Beyond 5G                                       |
| BS        | Base station                                    |
| CSI       | Channel state information                       |
| eMBB      | Enhanced mobile broadband                      |
| H-NOMA    | Heterogeneous non-orthogonal multiple-access    |
| H-OMA     | Heterogeneous orthogonal multiple-access        |
| I-CSI     | Instantaneous CSI                               |
| i.i.d.    | Independent and identically distributed         |
| IRS       | Intelligent reflecting surface                  |
| LoS       | Line-of-sight                                   |
| mMTC      | Massive machine type communication              |
| NLoS      | Non-line-of-sight                               |
| NOMA      | Non-orthogonal multiple-access                  |
| OMA       | Orthogonal multiple-access                      |
| RAN       | Radio access network                            |
| S-CI      | Statistical CSI                                 |
| SDN       | Software-defined network                        |
| SNR       | Signal-to-noise ratio                           |
| URLLC     | Ultra-reliable low-latency communications       |

### Table 3. List of Symbols.

| Symbol | Meaning                                          |
|--------|-------------------------------------------------|
| $\alpha$ | Path-loss exponent                             |
| $\beta_b$ | Path-loss between the BS-eMBB link             |
| $\beta_a$ | Path-loss of the BS-URLLC link                 |
| $\beta_0$ | Constant path-loss factor (direct link)        |
| $\beta_1$ | Constant path-loss factor (compound link)      |
| $e_b$ | Reliability requirement of the eMBB service     |
| $e_a$ | Reliability requirement of the URLLC service   |
| $\eta$ | Rician factor                                   |
| $\Gamma_b$ | Channel gain of the eMBB                      |
| $\Gamma_u$ | Channel gain of the URLLC                      |
| $\lambda$ | Wavelength                                      |
| $\phi_c$ | Angle of arrival to the IRS                    |
| $\phi_{BS,b}$ | Random phase in the LoS of the BS-eMBB link    |
| $\phi_{BS,a}$ | Random phase in the LoS of the BS-URLLC link   |
| $\phi_{IRS-BS}$ | Random phase in the LoS of the IRS-BS link   |
| $\phi_{IRS,b}$ | Random phase in the LoS of the IRS-eMBB link |
| $\phi_{IRS,a}$ | Random phase in the LoS of the IRS-URLLC link  |
| $\theta$ | Phase shift vector at the IRS                  |
| $\xi$ | Amplitude reflection coefficient                |
| $d_{BS,b}$ | BS-eMBB link distance                          |
| $d_{BS,a}$ | BS-URLLC link distance                         |
| $d_{IRS}$ | IRS-eMBB link distance                         |
| $d_{IRS,b}$ | IRS-URLLC link distance                        |
| $d_{IRS,a}$ | IRS-URLLC link distance                        |
| $F$ | Number of radio resources                       |
| $F_b$ | Number of radio resources allocated to the eMBB |
| $F_u$ | Number of radio resources allocated to the URLLC |
| $G_r$ | Receiver antenna gain                          |
| $G_t$ | Transmit antenna gain                           |
| $h_{NL,LoS}$ | Rayleigh fading of the BS to $i$ (for $i \in \{b, u\}$) link |
| $h_{IRS}$ | Rayleigh fading of the BS to IRS link           |
| $h_{IRS,b}$ | Rayleigh fading of the IRS to $i$ (for $i \in \{b, u\}$) link |
| $h_{IRS}$ | Channel vector between BS and $i$ (for $i \in \{b, u\}$) |
| $h_{IRS,b}$ | Channel vector between BS and IRS               |
| $h_{IRS,b}$ | Channel vector between IRS and $i$ (for $i \in \{b, u\}$) |
| $h_{IRS,a}$ | Deterministic LoS between BS and $i$ (for $i \in \{b, u\}$) |
| $h_{IRS,a}$ | Deterministic LoS between BS and $i$ (for $i \in \{b, u\}$) |
| $K$ | Number of eMBB users                            |
| $n_b$ | Number of symbols per minislot                 |
| $N$ | Number of elements at the IRS                   |
| $N_e$ | Number of elements in the vertical level at the IRS |
| $N_h$ | Number of elements in the horizontal level at the IRS |
| $p_{HOMA}$ | URLLC Outage probability for H-OMA strategy    |
| $p_{HOMA}^u$ | URLLC Outage probability for H-NOMA strategy   |
| $r_b$ | Achievable rate for a single eMBB user          |
| $r_a$ | Achievable rate of $F_b$ eMBB users             |
| $r_u$ | Achievable rate at the URLLC for H-OMA strategy |
| $r_u$ | Achievable rate at the URLLC for H-NOMA strategy |
| $S$ | Number of minislots                            |
| $x$ | Transmitted message                             |
| $(x_i, y_i)$ | BS position                                    |
| $(x_b, y_b)$ | eMBB position                                  |
| $(x_i, y_i)$ | IRS position                                   |
| $(x_u, y_u)$ | URLLC position                                 |
| $y$ | Received signal at the BS                       |
| $z$ | Noise vector                                    |

II. SYSTEM MODEL

We consider an uplink wireless system where $K$ single-antenna eMBB users and a single-antenna URLLC user com-
communicate with a single-antenna BS, in the presence of an IRS with $N = N_h \cdot N_v$ reflecting elements. We define $\xi_n \in [0, 1]$ and $\theta_n \in [0, 2\pi)$, for $n = 1, \ldots, N$, as the amplitude reflection coefficient and the phase shift of the $n$-th IRS element, respectively, such that $\Theta = \text{diag}(\xi_1 e^{j\theta_1}, \ldots, \xi_N e^{j\theta_N})$. In order to consider maximum signal reflection elements, we assume $\xi_n = 1 \ \forall n$, as in [18], [22].

In addition, following [10], we consider a time-frequency grid composed of $S$ minislots (in time) and $F$ radio resources (in frequency), as illustrated in Fig. 1. One time-slot is composed of $S$ minislots, and carries the amount of $n_c$ symbols per minislot. Due to the stringent latency requirement, we assume that the URLLC user CSI is not known (either at the BS or at the user) before transmission, as estimating the CSI requires a signaling overhead that would increase the latency and, consequently, could violate the URLLC requirements. On the other hand, since the eMBB traffic does not present such a stringent constraint in terms of latency, it is in general subject to a prior scheduling phase. Therefore, we assume that the CSI of the eMBB users is known at the BS before the user transmission. In addition, it is also assumed that the transmission of each eMBB user occupies the entire timeslot of a single radio resource while the URLLC transmission occupies only a single minislot, but spreading across a subset of $F_s \leq F$ frequency channels, as in [10].

The CSI acquisition in a scenario assisted by an IRS can be performed at least in two ways. First, the channels from the IRS to the BS/eMBB users can be separately estimated by deploying sensing devices at the IRS elements [23]–[25], while exploiting channel reciprocity. This approach can only be applied to TDD systems. Second, the cascaded eMBB-IRS-BS/BS-eMBB channel can be estimated at the BS [26]–[28]. Unlike the first approach, the cascaded approach can be applied to both TDD and FDD systems and is more practically appealing due to the lower hardware cost and energy consumption at the IRS, as the IRS is not equipped with active elements. Therefore, there are different channel estimation methods that can be considered for our scenarios, each one with different acquisition and processing complexities. However, the analysis of the most suitable approach is considered to be outside the scope of this work.

In this paper, we evaluate three different scenarios related to the position of the URLLC and eMBB users, as depicted in Fig. 2. Although such scenarios present some similar features, one can note that the signal received at the BS has a different formulation for each case, due to the fact some links involve the IRS and others do not. More specifically, the following configurations, in terms of the IRS assistance, are present in each scenario:

- **Scenario 1** - Fig. 2(a): IRS assists the URLLC user only;
- **Scenario 2** - Fig. 2(b): IRS assists the eMBB user only;
- **Scenario 3** - Fig. 2(c): IRS assists both users.

It is important to highlight that, although we consider $K$ eMBB users, in each radio resource $f$ only one eMBB user and/or one URLLC user can transmit depending on the multiple access strategy (H-NOMA or H-OMA) adopted.

The detailed system models of each one of the above scenarios are described next.

### A. IRS-AIDED URLLC COMMUNICATION

Fig. 2(a) illustrates Scenario 1, where we consider the communication between the URLLC user and the BS assisted by an IRS. In addition, we assume that $K$ eMBB users directly communicate with the BS. Thus, the signal $y_{s,f}$ received at the BS, corresponding to minislot $s \in \{1, \ldots, S\}$ and frequency channel $f \in \{1, \ldots, F\}$ is given by

$$y_{s,f} = \sqrt{\beta_{b,f}} h_{\text{BS}-b,f} x_{b,s,f} + \sqrt{\beta_u} h_{u,f} x_{u,s,f} + z_{s,f},$$

(1)

where the subscripts $b$ and $u$ refer respectively to the eMBB user and URLLC user, being $x_{i,s,f} \in \mathbb{C}^{1 \times n_i}$ (for $i \in \{b, u\}$) the transmitted message and $z_{s,f} \in \mathbb{C}^{1 \times n_i}$ the noise vector, whose entries are independent and identically distributed (i.i.d.) Gaussian random variables with zero mean and unit variance. In addition, $h_{\text{BS}-b,f} \in \mathbb{C}^{1 \times 1}$ denotes the channel fading between the BS and a eMBB user,

$$h_{u,f} = h_{\text{BS}-IRS,f} \Theta \text{H} h_{\text{IRS}-u,f} + h_{\text{BS}-u,f}^H,$$

(2)

where $h_{\text{BS}-IRS,f} \in \mathbb{C}^{1 \times N}$ denotes the fading vector between the BS and the IRS, $h_{\text{IRS}-u,f} \in \mathbb{C}^{N \times 1}$ is the fading vector...
between the IRS and the URLLC user, and $h_{\text{BS},u}^H, f \in \mathbb{C}^{1 \times 1}$ is the fading between the BS and the URLLC user.

In this paper, we consider the general Rician fading model [18] for all channels. Thus the fading in the BS-$i$ (for $i \in \{b, u\}$) and IRS-$j$ (for $j \in \{BS, b\}$) links are given by

$$h_{\text{BS},i} = \frac{1}{\sqrt{1 + \eta}} \left( \sqrt{\eta} h_{\text{BS},i}^{\text{Los}} + h_{\text{BS},i}^{\text{NLoS}} \right),$$

$$h_{\text{IRS},j} = \frac{1}{\sqrt{1 + \eta}} \left( \sqrt{\eta} h_{\text{IRS},j}^{\text{Los}} + h_{\text{IRS},j}^{\text{NLoS}} \right),$$

where $\eta$ is the Rician factor, $h_{\text{BS},i}^{\text{Los}} = e^{i \phi_{\text{BS},i}}$ and $h_{\text{IRS},j}^{\text{Los}} = e^{i \phi_{\text{IRS},j}}$ are the deterministic line-of-sight (LoS) components, where $\phi_{\text{BS},i} \in \mathbb{R}^{1 \times 1}$ and $\phi_{\text{IRS},j} \in \mathbb{R}^{N \times 1}$ represent the random phases in the LoS components. Moreover, $h_{\text{BS},i}^{\text{NLoS}}$ and $h_{\text{IRS},j}^{\text{NLoS}}$ are the non-LOS (NLoS) components, modelled as a complex Gaussian random variable with zero mean and unit variance (i.e. the NLOS component is Rayleigh fading).

In addition, $\beta_0$ is the path-loss between the BS and the URLLC user, and $\beta_{b,f}$ represents the path-loss between the BS and the eMBB user in the frequency channel $f$. Recall that, in this paper, we consider that there are $K$ eMBB users and that each one uses a different frequency channel. Moreover, for the sake of simplicity, we consider that $\beta_{b,f} = \beta_b \forall f$. It is important to highlight that the characteristics of the path-loss coefficients depend on whether the communication is established directly between users and the BS or through the IRS. Therefore, for Scenario 1, we can verify that $\beta_b$ should be computed for a direct path between the BS and the eMBB user, and it is given by [29]

$$\beta_b = G_t + G_r - 10 \alpha \log_{10}(d_{\text{BS,b}}) - \beta_0,$$

where $\beta_0$ is a constant path-loss factor, $\alpha$ is the path-loss exponent, $d_{\text{BS,b}}$ is the distance between the BS and the eMBB users, while $G_t$ and $G_r$ are respectively the antenna gains at the users and at the BS (in dBi). Moreover, $\beta_b$ must be computed considering the compound link (URLLC-BS-IRS), and it is given by [30]

$$\beta_a = G_t + G_r + 10 \log_{10}(D) - \beta_1,$$

where $\beta_1$ is a constant path loss factor,

$$D = \left( \frac{a b}{d_{\text{BS},\text{IRS}}^H d_{\text{IRS},u}^H} \right)^2 \cos^2(\phi_c)$$

where $d_{\text{IRS},u}$ is the distance between the IRS and the URLLC user, $a = N_b d_{\text{IRS}}$ and $b = N_c d_{\text{IRS}}$ are the IRS dimensions, $d_{\text{BS}}$ is the distance between the IRS elements, $\lambda$ is the wavelength, and $\phi_c = \arctan(y_0/x_0)$ denotes the angle of arrival to the IRS and $(x_0, y_0)$ is the BS location.

B. IRS-AIDED EMBB COMMUNICATION

Fig. 2(b) shows Scenario 2, where, differently from Scenario 1, we consider that the URLLC user communicates with the BS without the assistance of an IRS. In addition, we consider the IRS-aided communication between $K$ eMBB users and the BS, each in a different frequency channel. Therefore, the signal $y_{s,f}$ received at the BS, corresponding to minslot $s \in \{1, \ldots, 3\}$ and frequency channel $f \in \{1, \ldots, F\}$ is given by

$$y_{s,f} = \sqrt{\beta_b} h_{b,s,f} x_{b,s,f} + \sqrt{\beta_a} h_{\text{BS},u,f} x_{u,s,f} + z_{s,f},$$

where $h_{\text{BS},u,f} \in \mathbb{C}^{1 \times 1}$ is the fading between the BS and the URLLC user,

$$h_{b,f} = h_{\text{BS},\text{IRS},f} \Theta h_{\text{IRS},b}^H + h_{\text{BS},b,f}^H,$$

where $h_{\text{BS},\text{IRS},f} \in \mathbb{C}^{1 \times N}$ is the fading vector between the BS and IRS, $h_{\text{IRS},b,f} \in \mathbb{C}^{N \times 1}$ is the fading between the IRS and eMBB user, and $h_{\text{BS},b,f} \in \mathbb{C}^{1 \times 1}$ is the fading between the BS and eMBB user. Moreover, $h_{\text{BS},u,f}$ (for $i \in \{b, u\}$) is given by (3) and $h_{\text{IRS},f}$ (for $j \in \{BS, u\}$) is given by (4).

In addition, $\beta_b$ is computed considering the compound link (eMBB-BS-IRS), which is given by (6) but replacing $d_{\text{IRS},u}$ by $d_{\text{BS},u}$, where the latter is the distance between the eMBB user and the IRS. Moreover, $\beta_a$ is computed using (5), replacing $d_{\text{BS},b}$ by $d_{BS,u}$.

C. IRS-AIDED EMBB AND URLLC COMMUNICATION

The last evaluated scenario is shown in Fig. 2(c), where the communication between the BS and all users is assisted by an IRS. Thus, the signal $y_{s,f}$ received at the BS,
corresponding to minislot $s \in \{1, \ldots, S\}$ and frequency channel $f \in \{1, \ldots, F\}$ is
\[
y_{s,f} = \sqrt{\beta_u} h_{o,f} x_{s,f} + \sqrt{\beta_u} h_{u,f} x_{u,s,f} + z_{s,f},
\]
where, $h_{o,f}$ is given by (9) and $h_{u,f}$ by (2). Moreover, $h_{RS-i}$ (for $i \in \{b, u\}$) is as in (3) and $h_{IRS-j}$ (for $j \in \{BS, b, u\}$) as in (4). In this scenario, $\beta_o$ is given by (6) while $\beta_u$ is calculated in the same way but replacing $d_{IRS-0}$ by $d_{IRS-b}$.

III. RAN SLICING

Network slicing is an emerging technology that is expected to be fundamental in 5G wireless networks [31]–[33], guaranteeing the coexistence of heterogeneous services with different requirements. Network slicing allocates resources by means of software-defined networking (SDN) and network virtualization, “slicing” the network into logically isolated subnetworks [34]. More specifically, network slicing refers to the slicing of one physical network into multiple virtual networks, each of them designed and optimized for a specific service. In addition, from slicing the network, it is possible to maintain a minimum performance and isolation to active heterogeneous users in the same network [35] as all subnetworks have to appear to be a single network and each one has to guarantee certain features (e.g. latency and reliability) [34]. In order to better explain the concepts of this technology, Fig. 3 presents a conceptual illustration of network slicing [36].

As shown in Fig. 3, it is possible to describe the network slicing concept by three layers [36]. The first layer, “Service Instance Layer”, represents the 5G services (eMBB, URLLC, and/or mMTC services), which are allocated to each slice presented in the next layer. The second layer, “Network Slice Instance Layer”, represents the sliced network where each slice is allocated to one or more services in order to accommodate their requirements. Thus, each network slice may contain one or more isolated or shared subnetwork instances. To finish, the third layer, “Resources Layer”, represents the physical resources used by the services, which need to be smartly sliced due to the limited frequency spectrum resources [36]. In this paper, we focus on the Resource Layer, more specifically on the RAN physical layer, and we study the RAN slicing by means of orthogonal and non-orthogonal resource allocation among the eMBB and URLLC services. In addition, we explore the deployment of an IRS in the network, and we also place special emphasis on how to group the users based on their position in order to improve the system performance. We evaluate the three different scenarios depicted in Fig. 2 in terms of their achievable rate and clustering approach. The performance metric considered in this work, achievable rate, is detailed next.

A. PERFORMANCE METRIC: ACHIEVABLE RATE

The performance metric adopted in this work is the pair $(r_{sum,b}, r_u)$ of eMBB and URLLC achievable rates when subjected to the reliability constraints $(e_b, e_u)$, respectively. Thus, let $\Gamma_{i,f} = \beta_i |h_{i,f}|^2$ represent the composite channel gain of user $i \in \{b, u\}$. In H-OMA, $F_u$ channels are reserved exclusively to URLLC, while the remaining $F_b = F - F_u$ channels are allocated to the eMBB traffic only. In contrast, with H-NOMA all the channels are allocated simultaneously to both services, such that $F_b = F_u = F$. Moreover, in this paper we consider $K = F_b$ eMBB users and, as previously mentioned, each of them uses a different frequency resource $f$. The eMBB users are allocated to different channels by the BS in a process prior to transmission.

1) eMBB

Due to its rigorous latency constraint, the URLLC traffic is decoded first\(^2\). Moreover, due its very high reliability requirement $(e_b/e_u \sim 100$ in practice), it is reasonable to consider that the eMBB performance is not affected by the URLLC interference even in case of H-NOMA \(^{10}\). Moreover, since the eMBB traffic goes through a grant assignment process\(^3\), the achievable eMBB sum-rate, either under H-OMA or H-NOMA, is \(^{10}\)
\[
r_{sum,b} = F_u \sum_{f=1}^{F_u} r_{b,f} = F_u \sum_{f=1}^{F_u} \log_2 \left(1 + \Gamma_{b,f} \right),
\]
where $r_{b,f}$ is the achievable rate for a single eMBB user (or a single radio resource $f$).

2) URLLC

The outage probability of the URLLC user considering H-OMA and H-NOMA, is respectively,
\[
P_u^{H-OMA} = Pr \left\{ \frac{1}{F_b} \sum_{f=1}^{F_b} \log_2 \left(1 + \Gamma_{u,f} \right) < r_u^{H-OMA} \right\}
\]

\(^2\)In general, a pre-determined user decoding order is not optimal in NOMA systems. However, the decoding of a URLLC transmission cannot wait for the decoding of eMBB traffic \(^{10}\). In addition, even if latency was not an issue and we were to decode the eMBB user first, then the required eMBB reliability would have to be greater than or equal to that of URLLC.

\(^3\)The eMBB user is scheduled by the BS only when the current SNR is high enough to guarantee its reliability requirement.

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and
\[
\rho_u^{\text{H-NOMA}} = \Pr \left[ \frac{1}{F} \sum_{f=1}^{F} \log_2 \left( 1 + \frac{\Gamma_{u,f}}{\Gamma_{b,f}} \right) < r_u^{\text{H-NOMA}} \right],
\]
where the achievable rates \( r_u^{\text{H-NOMA}} \) and \( r_u^{\text{H-NOMA}} \) are obtained by imposing the constraints \( \rho_u^{\text{H-NOMA}} \leq \epsilon_u \) and \( \rho_u^{\text{H-NOMA}} \leq \epsilon_u \).

From (13), we can see that, in the case of URLLC, H-NOMA is sensitive to interference. More specifically, it depends on the channel gains of the eMBB users allocated in the same resource block, being thus dependent on which users are clustered together (user clustering approach [20]). Therefore, we evaluate the effect of clustering the users considering that each cluster is composed of \( K = F_b \) eMBB users and one URLLC user. In particular, we consider different clustering configurations based on the users’ distance to the BS and the IRS.

**B. IRS-BASED BEAMFORMING DESIGN**

A proper IRS-based beamforming design has the purpose of adjusting the phase shifts to optimize performance. However, the aforementioned design requires CSI availability at the BS. In this sense, we consider the beamforming design for each of the scenarios illustrated in Fig. 2 as follows.

1) **Scenario 1 (Fig. 2(a)):** When the IRS assists the URLLC user only, we adopt random phase shifts at the IRS, since CSI of the URLLC user is not known in advance at the BS. Although the URLLC user is not able to estimate its CSI, and, consequently, the optimal phase shifts at the IRS cannot be designed, some works have shown that the deployment of an IRS considering only random phase shifts at the IRS greatly increases the system performance, which justifies the IRS deployment [37] by greatly reducing the signaling and protocol overhead.

2) **Scenario 2 (Fig. 2(b)):** When the IRS is assisting the eMBB users only, once the CSI of the eMBB users are known at the BS, it is possible to define the optimal phase shifts by aligning the signal that passes through the eMBB-IRS and BS-IRS links with the signal over the eMBB-BS link [30], i.e.,
\[
\theta^* = \arg(h_{\text{BS-b}}) - \arg(h_{\text{BS-IRS}}) - \arg(h_{\text{IRS-b}}).
\]

3) **Scenario 3 (Fig. 2(c)):** When the IRS assists all users, the phase shifts are optimized with respect to the eMBB users, while appearing as random to the URLLC user.

**C. CLUSTERING APPROACHES**

The clustering of the users to be served in the same resources is one of the main issues in NOMA systems [38] and many approaches have been proposed so far [20], [39]-[41]. For instance, in [41], a joint clustering and power allocation method is proposed to optimize the achievable sum-rate with a minimum rate constraint, while in [42] such approach is successfully applied to a hybrid satellite-terrestrial network. Moreover, according to [20], [39]-[41], the typical clustering strategies consider two users per cluster (named user pairing [20], [40]) or multiple users per cluster. The choice of which clustering approach to be used depends on the scenario, including the type of communication system, number of users/services, and type of services.

Despite the clear importance of clustering strategies in NOMA systems, to the best of the authors’ knowledge, there is no study on clustering in scenarios with heterogeneous users involving the aid of an IRS. Therefore, in this paper, we evaluate different clustering configurations where heterogeneous services (eMBB and URLLC) are clustered based on the users’ average signal-to-noise ratio (SNR). For this type of scenario, a traditional clustering method cannot be readily applied as the URLLC stringent reliability requirement influences the decoding order. In this case, the decoding of a URLLC transmission cannot wait for the decoding of eMBB traffic and, consequently, the channel gain order of the users cannot be completely considered in the clustering strategy, as required in [38].

**IV. NUMERICAL RESULTS**

We consider the setup in Fig. 4, where \((x_0, y_0), (x_1, y_1), (x_u, y_u)\), and \((x_v, y_v)\) are the BS, IRS, eMBB, and URLLC positions, respectively. Therefore, \(d_{\text{BS-IRS}}, d_{\text{BS-b}}, d_{\text{IR-S-u}}, \) and \(d_{\text{IR-S-b}}\) are the BS-IRS, BS-URLLC, BS-eMBB, IRS-URLLC, and IRS-eMBB distances, respectively. Moreover, we consider the simulation parameters presented in Table 4. In addition, we fix \(N_0 = 10\) and vary \(N\) to define \(N = N_0 \times N_v\). It is important to mention that the numerical results are obtained using Matlab® and all curves present the average of 103 different realizations.

\[4\text{In this paper, for the sake of simplicity and for easier reproduction, we consider that the } K \text{ eMBB users are approximately at the same distance from the BS, therefore, } (x_b, y_b) \text{ represents the position of the } K \text{ eMBB users.}\]

\[5\text{As previous mentioned (Section III-A), for H-OMA, } F_b = F - F_u, \text{ and for H-NOMA, } F_u = F_b = F.\]
A. H-OMA AND H-NOMA ACHIEVABLE RATES

Fig. 5 presents the rate region \( (r_u, r_{\text{sum},b}) \) for the three scenarios depicted Fig. 2 considering different IRS sizes \( N \in \{60, 100\} \). The location of the eMBB and URLLC devices varies according to the scenario, and their position are presented in the caption of Fig. 5. First, Fig. 5(a) considers Scenario 1, where the IRS assists the URLLC user only. It can be seen that, for a fixed \( N \), in this scenario H-NOMA outperforms H-OMA throughout the entire rate region. Moreover, one can see that IRS considerably increases the URLLC rate. For instance, \( r_u \) is increased from \( \sim 0.3 \) bps/Hz to \( r_u \sim 0.7 \) bps/Hz in H-NOMA for \( r_{\text{sum},b} = 9.5 \) bps/Hz and \( N = 100 \). From another perspective, IRS can increase the eMBB sum-rate, as for instance when \( r_u = 0.5 \) bps/Hz, where H-NOMA strategy assisted by an IRS achieves an eMBB sum-rate of \( \sim 9.5 \) bps/Hz which represents an increase of \( \sim 90\% \) with respect to the IRS-free case.

In Fig. 5(b) we evaluate Scenario 2 (IRS assists the eMBB users). Due to the proper phase shift design enabled by the CSI availability, one can see that the eMBB performance is boosted by the IRS, considerably enhancing the eMBB achievable rate to values as high as \( r_{\text{sum},b} \sim 57 \) bps/Hz (for \( N = 100 \)), while the maximum achieved eMBB sum-rate is \( r_{\text{sum},b} \sim 4 \) bps/Hz in the scenario without IRS. In this scenario, however, there are situations where H-OMA achieves higher pair rates than H-NOMA, due to the fact that the URLLC user is neither close to the BS nor the IRS and the eMBB users are close to the IRS, which reduces the URLLC user’s channel gain, \( i.e., \Gamma_u < \Gamma_b \), reducing the performance of the URLLC user when considering the NOMA strategy as from (13). Finally, Fig. 5(c) considers Scenario 3, where all users are assisted by an IRS. In this scenario, we consider that all users are closer to the IRS than to the BS. From the results, considering \( N = 100 \), it is possible to increase in \( \sim 90\% \) and in \( \sim 50\% \) the eMBB and URLLC achievable rates, respectively, when compared to the case without IRS. In addition, one can see that increasing \( M \) considerably improves the performance of both scenarios. However, it is important to highlight that the

\begin{table}[h]
\centering
\caption{Simulation parameters.}
\begin{tabular}{|c|c|}
\hline
Parameter & Value \\
\hline
\( K \) & \( F_b \) \\
\( f_c \) & 4 GHz \\
\( \eta \) & 1 \\
\( d_{\text{bps}} \) & 0.5 \\
\( G_i, G_j \) & 3 dBi \\
\( \epsilon_a \) & 10^{-3} \\
\( \alpha \) & 2.2 \\
\( \beta_0 \) & 41.98 dB [29] \\
\( \beta_1 \) & 21.98 dB [30] \\
\( (x_0, y_0) \) & (80, 2) m \\
\( (x_1, y_1) \) & (0, 2) m \\
\hline
\end{tabular}
\end{table}

\*Recall that the rate region \( (r_u, r_{\text{sum},b}) \) is obtained from (11)-(13) [4]. More specifically, the rate region \( (r_u, r_{\text{sum},b}) \) is obtained by performing the following steps: (i) Compute/generate the path-loss and fading vectors given by (5)-(6) and (3)-(4), respectively; (ii) Compute the optimum phase shift vector at the eMBB users given by (14); (iii) For H-NOMA, we fix \( \Gamma_u, f \) and compute the maximum \( r_u \) while varying the eMBB channel gain from 0 to \( \Gamma_u f \). Moreover, in the case of H-OMA, the results consider the optimum \( (F_u, F_b) \) pair. (iv) The previous steps are performed for every independent channel realization and all curves present the average achievable rate at the eMBB and URLLC devices.
system complexity increases with $M$, establishing a trade-off.

In addition, in order to better illustrate the influence of the distance among network elements in the system performance, Figure 6 presents an analysis of Scenario 3 (Figure 2(c)) for different BS-eMBB users distance. We fix $r_u = 1.0$ bps/Hz and find $r_{sum,b}$ for different $d_{BS-b}$ values considering $N = 100$, $(x_i = 80, y_i = 2)$ m, $(x_i = 0, y_i = 2)$ m, and $(x_i = 10, y_i = 0)$ m. We can see that the achievable rate at the eMBB users decreases with $d_{BS-b}$ until $d_{BS-b} = 35$ m (eMBB users are close to the BS and far from the IRS), while it increases for $d_{BS-b} > 35$ m (eMBB users are far from the BS and close to the IRS) due to the IRS influence. From the results, we can observe the influence of the position of the network elements and we can also note that the deployment of an IRS can increase the system performance for users far from the BS.

![Analysis of the distance between the BS and the eMBB users.](image_url)

Table-5 presents the performance of the IRS-assisted system for different URLLC reliability values ($e_u \in \{10^{-5}, 10^{-6}\}$) considering Scenario 2 in Fig. 2(b). From the results, we can verify that the IRS can considerably increase the eMBB rate and the URLLC reliability for both strategies simultaneously. For example, while $r_{sum,b}^{OMA-IRS} = 22.7$ bits/Hz for $e_u = 10^{-6}$, the highest rate in the scenario without IRS is only $r_{sum,b}^{OMA} = 3.4$ bits/Hz for $e_u = 10^{-5}$.

### B. USER CLUSTERING ANALYSIS

In Fig. 5 one could see that the scenario heavily affects the system performance, and that adopting IRS to assist both users as depicted in Fig. 5(c) does not necessarily increase the rate when compared to Fig. 5(b), where only the eMBB users are assisted by the IRS. This happens because the distances between the IRS and the users in Fig. 5(c) are not ideal to fully exploit the IRS gain and to maximize the users SNR.

In this line, Fig. 7 considers the scenario in Fig. 2(c), but now assuming $(x_i = 10, y_i = 0)$ m and $(x_i = 70, y_i = 0)$ m in Fig. 7(a), and $(x_i = 70, y_i = 0)$ m and $(x_i = 10, y_i = 0)$ m in Fig. 7(b), i.e., one user (URLLC or eMBB) is close to the BS and the other (eMBB or URLLC) is close to the IRS, while both are being assisted by the IRS.

From Fig. 7(b), we can see that when the eMBB users are close to the IRS and the URLLC user is close to the BS, it is possible to considerably increase the URLLC achievable rate with respect to Fig. 5(b) and, when compared to Fig. 5(a), it is possible to greatly increase both the eMBB and URLLC achievable rates. However, when the eMBB users are close to the BS and the URLLC user is close to the IRS, as depicted in Fig. 7(a), the URLLC user presents a smaller achievable rate when compared to the scenario in Fig. 7(b). This is due to the impossibility to properly adjust the phase shifts due to the unavailability of CSI of URLLC, and consequently the IRS gain is not fully exploited. However, we can verify that, although the phase shifts at the IRS are randomly defined, the use of an IRS improves the URLLC achievable rate, which justifies the deployment of an IRS in the future networks.

In addition, in Fig. 7, we include the impact of considering random phase shifts at the IRS (i.e., without optimizing the phase shifts for the eMBB user), which illustrates the importance of the proper design, mainly when the eMBB user is closer to the BS.

Therefore, it is evident that proper user clustering has a great impact in the performance of H-NOMA. Based on our extensive numerical evaluation, we can list the following observations in the case of RAN slicing aided by an IRS:

- When all users are far from the BS and IRS (not shown here), they achieve a very small rate for both H-OMA and H-NOMA strategies, due to the high path loss of the compound links. Therefore, clustering users far from the BS and IRS is not a proper solution.

- When all users are close to the IRS (Fig. 2(c)) or when the eMBB users are close to the BS and far from the IRS and the URLLC user is close to the IRS and far from the BS (Fig. 7(a)), it is possible to achieve a high eMBB sum-rate and a reasonable URLLC rate. Therefore, in terms of clustering strategy, in the lack of better options, these relative user positions should be considered as an alternative to avoid pairing users that are both far from the BS and IRS.

- When the eMBB users are close to the IRS and the URLLC user is close to the BS (Fig. 7(b)), eMBB achieves a high sum-rate while guaranteeing high reliability and a relatively high rate for the URLLC user. Therefore, giving the requirements of both services, this clustering approach is the best option for exploiting the most of RAN slicing between eMBB and URLLC traffic with the aid of an IRS.

Therefore, we can conclude that the best user clustering strategy consists of: (1) First, to group the eMBB users close to the IRS with URLLC users close to the BS; (2) Second, the other users should be paired considering two options: (i) To group eMBB users close to the BS with URLLC users close to the IRS; (ii) To group eMBB users close to the BS with eMBB users far from the IRS.
the IRS; or (ii) To group eMBB and URLLC users close to the IRS; (3) The remaining users should be clustered considering the distance between them, as in the best user clustering strategies the eMBB and URLLC users are relatively distant from each other to limit interference\(^8\). In addition, for the H-NOMA strategy, as in accordance to [10], it is important to guarantee that \( \Gamma_u > \Gamma_h \), otherwise H-OMA may be more advantageous.

\(^8\)It is important to highlight that, in this paper, we do not consider the scenario where both the eMBB users and the URLLC users are close to the BS, as in this case the IRS is not essential for achieving a good performance.

C. IMPERFECT PHASE SHIFT AT THE IRS

The previous results consider perfect phase shift at the IRS which is very idealistic and that imperfect phase knowledge should be considered. In this sense, Table 6 presents the performance of the proposed solution considering the impact of imperfect estimation of the phase at the IRS elements, where \( \tau \) is a uniform random phase shift error, expressed in percentage, with respect to the actual phase. From the results, we can verify that the imperfect phase shift at the IRS elements degrades the performance, but the proposed solution assisted by an IRS still achieves a considerably better performance than the system without an IRS. For example, while \( r_{\text{sum,b}}^{\text{OMA-IRS}} = 46.1 \text{ bits/Hz} \) for \( \tau = 40\% \), the rate in the scenario without IRS is only \( r_{\text{sum,b}}^{\text{OMA}} = 3.9 \text{ bits/Hz} \). Therefore, the importance of considering an IRS to support heterogeneous devices in the same network is reinforced by the above results.

D. INFLUENCE OF THE Rician FACTor

In order to illustrate the performance of the proposed solution for different channel conditions, Table 7 presents the sum rate for different Rician factors. More specifically, we consider the Scenario 3 in Fig. 2(c) for \( \eta_{\text{BS-u}} = \eta_{\text{IRS-u}} = \eta_{\text{BS-IRS}} = 1 \), and vary \( \eta_{\text{BS-b}} \) and \( \eta_{\text{IRS-b}} \). From the results, we can verify that for a scenario with high influence of the LoS components the performance of the proposed solution increases, as expected. In addition, it is possible to observe that the proposed solution is robust enough to support heterogeneous services even in a scenario with high influence of the NLoS components.

Finally, we end this section by noting that for different scenarios and users’ positions a specific multiple access strategy (H-NOMA or H-OMA) performs best. Thus, a hybrid NOMA/OMA scheme can be considered in order to guarantee the maximum system performance at all times, as in [39], [40]. However, as we consider two heterogeneous services, there is a trade-off between the eMBB and URLLC performance and, in order to deploy a hybrid H-NOMA/H-OMA scheme, it is necessary to define constraints for each type of service in

![Graph](image-url)
order to define the maximum system performance taking into account both the eMBB and URLLC stringent requirements.

V. CONCLUSIONS

In this paper, we considered the deployment of an IRS to assist the communication between two heterogeneous services and a common BS. In addition, we evaluated the RAN slicing considering the H-OMA and H-NOMA strategies. From the results, we can conclude that the deployment of an IRS can considerably increase the eMBB and URLLC achievable rates. Moreover, we also provided some insights on the best user clustering strategy showing that the best option is to match eMBB users close to the IRS with URLLC users near the BS, as in this case the eMBB users can achieve a high data rate while guaranteeing high reliability and a considerable data rate to the URLLC user. As future works, the following problems could be investigated:

- As the URLLC services are not able to estimate the instantaneous CSI (I-CSI) and, consequently, the optimal phase shifts design is not feasible, the estimation of the statistical CSI (S-CSI) could be explored to compute the sub-optimal phase shifts at the IRS in order to improve the URLLC achievable rate.
- Different scheduling and pairing strategies can be studied to maximize the spectrum efficiency by dividing the spectrum into many portions, where different pairing or even multiplexing strategies may be used in each of them.
- Finally, network slicing between the eMBB and mMTC services could be studied. In addition, the clustering approaches presented in this paper could be evaluated for eMBB and mMTC services, considering their respective requirements and features.

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