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# On the outage probability of uplink IRS-aided networks: NOMA and OMA

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ABSTRACT

In this paper, the outage performance of uplink intelligent reflecting surface (IRS)-aided non-orthogonal and orthogonal multiple-access (NOMA/OMA) networks is investigated. Specifically, we consider a two-user equipment (UE) NOMA/OMA network, in which both UEs have both direct (UE→base station (BS)) and reflected (UE→IRS→BS) links. All the links between the UEs and the IRS/BS are modeled either as a Rayleigh or a Nakagami-$m$ variate. To characterize these networks' outage performance, new statistics for the effective channel gains of the IRS-NOMA/OMA's UEs are derived. Based on that, closed-form expressions for the outage probability (OP) for each UE are derived. Monte Carlo simulations' results are provided to verify the accuracy of the analytical results.

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## 1. Introduction

According to the CISCO's annual internet report [1], by 2023 more than 2 billion mobile devices are expected to be connected to the mobile network, where 10% of it will benefit from the fifth-generation (5G) wireless network's services. In the near future, the data traffic will be shared among all sorts of devices including smartphones, wearable devices, smart cars, …etc. As a result, the current communication networks are to be updated and improved to fulfill the requirements of future developments. Massive machine-to-machine (M2M) communications will accompany these updates and improvements and will enable the development of the internet of things (IoT). Eventually, the IoT will help to integrate different technologies into a unified service for which the core will be the user himself.

The 5G wireless notworks are supposed to implement various enabling technologies such as millimeter waves, ultra-dense networks, massive multiple-input multiple-output (MIMO), …etc. Among the constraints underlying these technologies is the difficulty to control the radio propagation environment while ensuring a low cost and a high energy/spectral efficiency (EE/SE). Intelligent reflecting surfaces (IRSs) [2,3], re-configurable intelligent surfaces (RISs) [4], software-controlled meta-surfaces (SCMs) [5–7] and software-defined hyper-surfaces (SDHSs) [8] are all a sort of real-time re-configurable reflect-arrays. They are thus used as a cost-effective and energy/spectral efficient solution to intelligently adapt the mobile user's propagation environment with the aim of improving the reception reliability and the user's data rate [2,3,7,9]. An IRS basically differs from the half-duplex (HD) relay in the point that it just reflects and beam-forms the incident signal instead of actively processing it, so it consumes less energy. It can also perform in a full-duplex (FD) mode without self-interference [3].

As a multiple-access (MA) technique, non-orthogonal MA (NOMA) allows the mobile users to dynamically share the available spectrum, which helps to reduce the access latency, increase the SE, support more connectivity and improve the users' fairness [10] with the cost of an increase in the receiver's complexity compared to orthogonal MA (OMA). A natural direction was to combine these two technologies to ensure an effective and intelligent adaptation of the NOMA users' propagation environment and benefit at the same time from the advantages of NOMA in facilitating the spectrum sharing among those users [11–14]. In the literature, this combination is called IRS-aided NOMA, IRS-assisted NOMA or simply IRS-NOMA.

### 1.1. Related works

IRS-NOMA has attracted a huge interest both in academia and industry. For instance, in order to achieve an appropriate trade-off between maximizing the sum rate and minimizing the total power consumption in a downlink multiple-input-single-output (MISO) IRS-NOMA network, an energy-efficient algorithm was proposed in [11]. Ref. [12], has introduced a special design of an IRS-NOMA network in which the near users are managed by

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space division multiple access (SDMA) while multiple IRSs are used to serve the additional cell-edge users. The sensitivity of this IRS-NOMA design to hardware impairments was also examined in the same work. In [13], the authors have proposed a priority-oriented design to improve the SE, in which the performance of the strongest user equipment (UE) was improved, whilst all other users benefited from IRS-assisted beam-forming. A performance comparison between NOMA and OMA in an IRS-assisted downlink configuration was carried-out in terms of the required transmit power, in [15]. In order to maximize the system's throughput of downlink IRS-NOMA network, the authors of [16] have formulated a joint optimization problem involving the channel assignment, the NOMA users' decoding order, the reflection coefficients and the power allocation. The effect of coherent phase shift and random phase shift design on the outage performance of a downlink IRS-NOMA network was investigated in [17]. To ensure user fairness, the authors of [18] have maximized the signal-to-interference-plus-noise ratio (SINR) of all users through the joint optimization of the phase-shift matrix at the IRS and the transmit beamforming vectors at the base station (BS). In [19], for a downlink IRS-NOMA network, the outage probability (OP) and the ergodic rate (ER) of users under perfect/imperfect successive interference cancellation (SIC) were investigated where a 1-bit coding scheme is considered.

The previously-mentioned works have dealt with the downlink case of IRS-NOMA networks [11–19]. The studies on the uplink IRS-NOMA network remained limited. In particular, the sum rate maximization problem for an uplink IRS-NOMA network was investigated in [20], where the authors considered a joint optimization of the phase-shift matrix at the IRS and the transmit power at the users for maximizing the sum rate of all users under individual power constraints. To solve the formulated non-convex problem, a semi-definite relaxation (SDR)-based solution was developed. The authors of [14] have investigated both downlink and uplink IRS-aided NOMA and OMA networks, in which they have deployed an IRS unit to improve the coverage of the cell-edge user. To evaluate this network's performance, they have introduced new channel statistics for the reflected link, which they have used latter to derive closed-form expressions for the OP and the ER. The outage performance for an uplink IRS-NOMA with continuous phase shifts was studied in [21], where the authors have approximated the users' received powers as a Gamma distributed random variable (RV), to be able to derive latter a closed-form expression for the OP. In [22], to analyze the performance of an uplink/downlink IRS-NOMA wireless powered communication network (WPCN), a sum-rate minimization problem was formulated and solved.

### 1.2. Motivation and contributions

In spite of the huge interest IRS-NOMA has gained [11–22], in most of the previous works at least one of the UEs is either served using the direct or the reflected link only but not by both of the links. To the best of the authors' knowledge, [21] is the first paper considering a two UE uplink IRS-NOMA in which both the UEs have both the direct and reflected links. Unfortunately, its analytical results are limited to the case of links undergoing Nakagami-$m$ fadings with spread parameters equal to unity, so it cannot handle the system's performance for other values of spread parameters. Also, the numerical results in [21], only cover the OP as a function of the outage threshold. Furthermore, its authors have used a rather complex and obscure parallel detection scheme. In this work, we adopt the NOMA's conventional serial decoding scheme (in the sense that the strong UE is decoded first by regarding the signal of the weak UE as interference) and we provide a more comprehensive analytical framework where many special-case scenarios (For instance, the cases of whether there is or there is no direct/indirect link between the UE and the BS for each UE, and the IRS-OMA case) can be easily derived. The following specific contributions are made:

- By considering the decoding rule previously described above and detailed later in Section 2, we introduce a SINR and a SNR formulas (which account for both the direct and reflected links) for $UE_1$ and $UE_2$, respectively.
- The fact that our system's model considers a generalized case in which both UEs have both direct and reflected links, has made the mathematical development (the statistics of the effective channel gains) intractable. To overcome this obstacle, we have had recourse to the Moments matching (MM) method (See Lemma 1 in Section 3.1). Using it we have derived in Section 3 new statistics for the effective channel gains of both IRS-NOMA/OMA's UEs (see Lemmas 2–8 in Section 3.2) which has served later in the derivation of new generalized closed-form expressions for the OPs of $UE_1$ and $UE_2$ of the network in consideration for both IRS-NOMA and IRS-OMA cases (See Theorems 1, 2 and 3 in Section 4).
- Note that, in our analytical results, the channel magnitude of each one of the links (between the UEs and the IRS/BS) can be modeled either as a Rayleigh or a Nakagami-$m$ variate. Also, for each UE, we can consider, as a special case, that only one or both links (direct and reflected) exist. Based on these considerations many different scenarios can be covered as special cases from our analytical results. Specifically, we consider two scenarios based on the channel conditions of the weak user's ($UE_2$) direct link: *(i)* poor channel conditions with a Rayleigh fading; and *(ii)* better channel conditions with a Nakagami-$m$ fading. The simulation results reveal that as the weak user's channel conditions get better, its outage performance improves while negatively impacting the strong user's ($UE_1$) OP.
- To evaluate the performance of the considered networks in a realistic outdoor transmission environment, we adopt the 3GPP Urban Micro (UMi) path loss model [23–25]. Moreover, we conduct in-depth discussions on the impact of different key parameters such as the number of elements in the IRS unit, the target rates, the fading parameters, and the users' transmit powers on the outage performance.

In Table 1, we synthesize the previous works which have adopted the MM method in approximating the OPs of some IRS-assisted networks.

**Table 1**
Existing works which have used the MM method to approximate the OPs of IRS-assisted networks.

| Ref. | Reflected links' fading | Direct link's fading | MA technique |
|---|---|---|---|
| [26,27] | Rayleigh | – | – |
| [28–30] | Rayleigh | Rayleigh | – |
| [31] | Rician | Rician | – |
| [32] | $\kappa - \mu$ | $\kappa - \mu$ | – |
| [33] | Rayleigh | Rayleigh | OMA |
| [21] | Nakagami-$m$ | Nakagami-$m$ | NOMA |
| This work | Rayleigh/Nakagami-$m$ | Rayleigh/Nakagami-$m$ | NOMA/OMA |

### 1.3. Organization and notations

The remainder of this paper is organized as follows. The system and channel models of the uplink IRS-aided NOMA/OMA networks are presented and described in the next section. Some key results developed to derive new statistics for the effective channel gains of both UEs are presented in Section 3. These results will