Analysis of Uplink IRS-Assisted NOMA under Nakagami-\(m\) Fading via Moments Matching

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Abstract—This letter investigates the uplink outage performance of intelligent reflecting surface (IRS)-assisted non-orthogonal multiple access (NOMA). We consider the general case where all users have both direct and reflection links, and all links undergo Nakagami-\(m\) fading. We approximate the received powers of the NOMA users as Gamma random variables via moments matching. This allows for tractable expressions of the outage under interference cancellation (IC), while being flexible in modeling various propagation environments. Our analysis shows that under certain conditions, the presence of an IRS might degrade the performance of users that have dominant line-of-sight (LOS) to the base station (BS), while users dominated by non-line-of-sight (NLOS) will always benefit from it.

I. INTRODUCTION

For beyond fifth-generation (B5G) wireless networks, intelligent reflecting surfaces (IRSs) have been identified as a key technology to enhance the spectral- and energy-efficiency at low-cost [1], [2]. Consisting of a large number of reconfigurable nearly-passive elements, those surfaces can alter the propagation of the incident waves to improve the wireless technology to enhance the spectral- and energy-efficiency at low-cost [1], [2].

Existing works on IRS-assisted NOMA transmission show promising gains in terms of the outage performance and sum-rate, e.g., [5]–[7], [9]. However, most of those works consider propagation under certain conditions, such as the weak NOMA user equipment (UE) being connected to the base station (BS) only via the IRS (no direct link), while the strong UE is only served by the direct link to the BS, with no contribution from the IRS. Another common assumption is Rayleigh fading, which is not a practical model for such systems, since the IRS could be deployed at buildings with strong line-of-sight (LOS) to the serving BS [2]. Also, in the context of NOMA user-pairing, the strong NOMA UE might have a good LOS to the BS, and possibly to the surface as well.

In this work, we consider a general two-UE IRS-NOMA uplink in which both UEs have direct and reflection links to the BS, and all the links undergo Nakagami-\(m\) fading. By adjusting the \(m\) parameter, we can easily switch between various LOS and non-line-of-sight (NLOS) propagation conditions. In order to obtain tractable expressions for the outage under NOMA interference cancellation (IC), the received powers of the NOMA UEs are approximated as Gamma random variables (RVs) via moments matching. Note that the Gamma power approximation has been applied before, e.g., in [10] to model the received power of IRSs for an orthogonal multiple access (OMA) setting under Rayleigh fading. We consider two strategies in which the IRS is either configured to boost the first UE, or the second one, and characterize the corresponding channel statistics and outage probability under IC. We apply our analysis to an example scenario, and show that under certain conditions, the presence of the IRS might degrade the outage performance of the UEs with dominant LOS to the BS.

II. SYSTEM MODEL

We consider a NOMA uplink with two UEs, assisted by an \(N\)-elements IRS. At the BS, the overall received signal from both the direct and reflection links is given by

\[
r = \sum_{i=1}^{2} \left( \sqrt{h_{i}} + \sqrt{P_{i}} \right) x_{i} + w,
\]

where \(h_{i} \in \mathbb{C}, h_{BS} \in \mathbb{C}^{N},\) and \(g_{i} \in \mathbb{C}^{N}\) are the small-scale fading coefficients of the UE-BS, BS-IRS, UE-IRS links, respectively. The parameters \(\ell_{h_{i}}, \ell_{BS},\) and \(\ell_{g_{i}}\) are the corresponding pathlosses, \(P_{i}\) and \(x_{i}\) are the transmit power and signal of the \(i^{th}\)-UE, and \(w\) is the zero-mean Gaussian noise with power \(P_{w}\). The matrix \(\Phi \in \mathbb{C}^{N \times N}\) is defined as

\[
\Phi = \text{diag}(e^{j\phi_{1}}, e^{j\phi_{2}}, \ldots, e^{j\phi_{N}}),
\]

where \(\phi_{n}\) is the phase-shift applied at the \(n^{th}\)-element of the IRS. Note that the IRS term can be written equivalently as

\[
h_{BS}^{T} \Phi g_{i} = \sum_{n=1}^{N} e^{j\phi_{n}} h_{BS,n} g_{i,n},
\]

where \(h_{BS,n}\) and \(g_{i,n}\) are the \(n^{th}\)-elements of \(h_{BS}\) and \(g_{i}\), respectively. The links are assumed to undergo Nakagami-\(m\) fading, i.e., \([h_{i}] \sim \text{Nakagami}(m_{h_{i}})\), \([h_{BS,n}] \sim \text{Nakagami}(m_{BS})\), \([g_{i,n}] \sim \text{Nakagami}(m_{g_{i}})\), where \(m_{h_{i}}, m_{BS}\), and \(m_{g_{i}}\) are the corresponding distribution parameters. On top of being a general fading distribution, Nakagami-\(m\) has a Gamma distributed power, and therefore some of the results we obtain below become exact under certain conditions.

We consider the case where the IRS is configured to boost the received power of either of the UEs. To maximize the receive power of the \(i^{th}\)-UE, the phase-shifts are set to

\[
\phi_{n} = \arg(h_{i}) - \arg(h_{BS,n} g_{i,n}),
\]
which can be shown by a simple application of the triangular inequality on the received amplitude. Since the Gamma moments matching is used frequently in this work, we state how it is performed in the following lemma.

**Lemma 1.** Let $X$ be a non-negative RV with first and second moments given by $\mu_X = \mathbb{E}\{X\}$ and $\mu_X^{(2)} = \mathbb{E}\{X^2\}$, respectively. The Gamma RV $Y \sim \Gamma(k, \theta)$ with the same first and second moments has shape $k$ and scale $\theta$ parameters

$$k = \frac{\mu_X^{(2)}}{\mu_X^2 - \mu_X^2}, \quad \theta = \frac{\mu_X^{(2)} - \mu_X^2}{\mu_X}.$$

Additionally, Gamma RVs have the scaling property, in the sense that if $Y \sim \Gamma(k, \theta)$, then $cY \sim \Gamma(k, c\theta)$.

### III. Statistics of the Received Power

Our goal is to obtain expressions that describe the outage probability of the $i$th-UE. In the presence of the interference from the other $j$th-UE, the signal-to-interference-plus-noise ratio (SINR) outage is defined as

$$p_{\text{out}}^{(i)} = \mathbb{P}\left\{ \frac{Z_i P_i}{Z_j P_j + P_w} \leq \epsilon \right\},$$

where $Z_i$ and $Z_j$, as defined below in (7) and (12), are the effective channel powers of the UEs, and $\epsilon$ is the outage threshold. If the interference is removed via IC, then the outage is defined for the signal-to-noise ratio (SNR) as

$$p_{\text{out, SNR}}^{(i)} = \mathbb{P}\left\{ \frac{Z_i P_i}{P_w} \leq \epsilon \right\},$$

which is simply the cumulative distribution function (CDF) of $Z_i$ evaluated at $\epsilon P_w / P_i$. In order to evaluate those probabilities, an access to the distributions of $Z_i$ and $Z_j$ is required, which are difficult to characterize, let alone obtaining exact closed-form expressions from them. For that reason, we resort to approximating the received powers as Gamma RVs via moment matching. On the one hand, the Gamma distribution encompasses many power distributions as special cases, and on the other hand, it allows for tractability when evaluating the outage. To do so, we need access to the moments of $Z_i$ and $Z_j$, for which we first need to characterize their statistics.

Next, and without loss of generality, we assume that the IRS is configured to boost UE1. In this case, the signal of UE1 will be coherently combined, while for UE2, and assuming the channels of the two UEs are uncorrelated, the combining will be fully random. The other case is simply obtained by a switch of indices.

#### A. Statistics of the Coherently Combined UE

Since the IRS is configured for UE1, its signal will be coherently combined, and therefore its effective channel power is given by

$$Z_1 = \left( \sqrt{\ell_{h_1}} |h_1| \right) + \sqrt{\ell_{BS} \ell_{g_1}} \sum_{n=1}^{N} \left| h_{BS,n} \right| \left| g_{1,n} \right| ^2,$$

Due to the coherent combining in (4), all the fading terms are in-phase aligned, and are positive-valued. The first term $|h_1|$ is Nakagami distributed. Therefore, in the absence of the second term, the receive power will be exactly Gamma (e.g., due to a high pathloss of the UE-IRS link). For the second term, it is a sum of unit-power double-Nakagami RVs. By the causal form of the central limit theorem (CLT) [11], we can approximate the sum of positive RVs by a Gamma RV. This is given by the following lemma (similar approximation for Rayleigh fading has been applied in [12]).

**Lemma 2.** Let $S_1 = \sum_{n=1}^{N} \left| h_{BS,n} \right| \left| g_{1,n} \right|$, then the distribution of $S_1$ can be approximated as

$$S_1 \approx \Gamma \left( N \frac{\mu_1^2}{1 - \mu_1^2}, \frac{1 - \mu_1^2}{\mu_1} \right),$$

with

$$\mu_1 = \frac{\Gamma(m_{BS} + \frac{1}{2}) \Gamma(m_{g_1} + \frac{1}{2})}{\Gamma(m_{BS}) \Gamma(m_{g_1}) (m_{BS} m_{g_1})^{1/2}},$$

where $\Gamma(\cdot)$ is the Gamma function.

**Proof.** We approximate the sum by a Gamma RV via Lemma 1. For that, we need the first and second moments of the sum. Note that the denominator of $k$ and the numerator of $\theta$ in Lemma 1 are the variance, which is easier to calculate here. The mean and variance of the sum under i.i.d. conditions are given by

$$\mu_{S_1} = \sum_{n=1}^{N} \mathbb{E}\{|h_{BS,n}| |g_{1,n}|| = N \mu_1,$$

$$\mu_{S_1}^2 - \mu_{S_1}^2 = \sum_{n=1}^{N} \text{Var}\{\left| h_{BS,n} \right| \left| g_{1,n} \right| \} = N (1 - \mu_1^2),$$

with

$$\mu_1 = \mathbb{E}\{\left| h_{BS,n} \right| \left| g_{1,n} \right| \} = \mathbb{E}\{\left| h_{BS,n} \right|\} \mathbb{E}\{|g_{1,n}||$$

being the product of the mean of two independent Nakagami RVs. By substitution of the values, we arrive at the final result. \qed

The quality of this Gamma approximation improves with the number of IRS elements. Figure 1 shows the density in log-scale for $N = 4$. As can been seen, the approximation holds very well even in the case of only four elements.

Let $H_{1,d} = \sqrt{\ell_{h_1}} |h_1|$ and $H_{1,r} = \sqrt{\ell_{BS} \ell_{g_1}}$ be the pathloss-scaled fading coefficients of the direct and reflection links, the channel power of UE1 can now be written as

$$Z_1 = (H_{1,d} + H_{1,r})^2.$$
Using the scaling properties of Nakagami and Gamma RVs, they are then distributed as

\[ H_{1,d} \sim \text{Nakagami}(m_{h_1}, \ell_{h_1}) \], (9)

\[ H_{1,r} \sim \Gamma(k_{S_1}, \sqrt{\ell_{BS}g_1} \theta_{S_1}) \], (10)

where \( k_{S_1} \) and \( \theta_{S_1} \) are the shape and scale parameters calculated via Lemma 2. Finally, we approximate \( Z_1 \) by our originally intended Gamma RV. Again, we need access to the first and second moments. Those are given under independence by the following lemma.

**Lemma 3.** The first two moments of UE1 channel power (under coherent combining) are given by

\[
\mu_{Z_1} = \mu_{H_{1,d}}^{(2)} + \mu_{H_{1,r}}^{(2)} + 2\mu_{H_{1,d}} \mu_{H_{1,r}}, \\
\mu_{Z_1}^{(2)} = \mu_{H_{1,d}}^{(4)} + \mu_{H_{1,r}}^{(4)} + 6\mu_{H_{1,d}} \mu_{H_{1,r}}^{(2)} + 4\mu_{H_{1,d}} \mu_{H_{1,r}}^{(3)},
\]

where

\[
\mu_{H_{1,d}}^{(p)} = \frac{\Gamma(m_{h_1} + \frac{p}{2})}{\Gamma(m_{h_1}/\ell_{h_1})^{p/2}}, \\
\mu_{H_{1,r}}^{(p)} = \frac{\Gamma(k_{S_1} + p)(\sqrt{\ell_{BS}g_1} \theta_{S_1})^p}{\Gamma(k_{S_1})}.
\]

**Proof.** Proof follows directly by expanding (8) and substituting the moments of Nakagami and Gamma RVs.

After scaling with \( P_1 \), the UE1 receive power follows the distribution

\[ Z_1P_1^{\text{approx}} \sim \Gamma(k_1, P_1 \theta_1), \]

where \( k_1 \) and \( \theta_1 \) are the Gamma RV parameters matched to the moments in Lemma 3.

**B. Statistics of the Randomly Combined UE**

Assuming the channels of the users are uncorrelated, the combining will appear random for UE2. In that case, the effective channel power of UE2 is given by

\[
Z_2 = \sqrt{\ell_{h_2}h_2 + \ell_{BS}g_2} \sum_{n=1}^{N} e^{j\phi_n}h_{BS,n}g_{2,n}^2 \right)^2. \]

Compared to (7), the sum term consists of out-of-phase complex-valued coefficients. Similarly to the previous subsection, we attempt to fit the sum by a simple distribution; namely, a complex-Gaussian through the conventional CLT.

**Lemma 4.** Let \( S_2 = \sum_{n=1}^{N} e^{j\phi_n}h_{BS,n}g_{2,n}^2 \), then the distribution of \( S_2 \) can be approximated as

\[ S_2^{\text{approx}} \sim \mathcal{CN}(0, N), \]

**Proof.** Proof follows by application of the CLT; see results for random combining in [9]. Although it is given there for the Rayleigh fading case, it holds here for Nakagami as well.

To investigate how good such an approximation is, we compare the magnitude of the sum with a Rayleigh fit. This is shown in Figure 2 for \( N = 4 \). We see that it does provide a good fit; however, it is not as good compared to the Gamma approximation in the case before.

We proceed next in a similar fashion as in the coherent combining case. Let \( H_{2,d} = \sqrt{\ell_{h_2}h_2} \) and \( H_{2,r} = \sqrt{\ell_{BS}g_2} \), be the pathloss-scaled fading coefficients of the direct and reflection links, the channel power of UE2 can be written as

\[ Z_2 = |H_{2,d} + H_{2,r}|^2. \]

The distribution of the magnitudes is given by

\[ |H_{2,d}| \sim \text{Nakagami}(m_{h_2}, \ell_{h_2}), \]

\[ |H_{2,r}| \sim \text{Nakagami}(1, N\ell_{BS}g_2), \]

where the fact that Nakagami becomes Rayleigh for \( m = 1 \) has been applied here to unify notation. We make no assumptions with respect to the phase distribution of the direct link; however, for the reflection link \( H_{2,r} \), its phase distribution is assumed to be zero-mean symmetric. This is a valid assumption due to the random combining of the sum terms.

Now, we apply the Gamma approximation of the power for \( Z_2 \). The first and second moments under independence are given by the following lemma.

**Lemma 5.** The first two moments of UE2 channel power (under random combining) are given by

\[
\mu_{Z_2} = \mu_{|H_{2,d}|}^{(2)} + \mu_{|H_{2,r}|}^{(2)}, \\
\mu_{Z_2}^{(2)} = \mu_{|H_{2,d}|}^{(4)} + \mu_{|H_{2,r}|}^{(4)} + 4\mu_{|H_{2,d}|} \mu_{|H_{2,r}|}^{(2)},
\]

where

\[
\mu_{|H_{2,d}|}^{(p)} = \frac{\Gamma(m_{h_2} + \frac{p}{2})}{\Gamma(m_{h_2}/\ell_{h_2})^{p/2}}, \\
\mu_{|H_{2,r}|}^{(p)} = \Gamma(\left(1 + \frac{p}{2}\right)(N\ell_{BS}g_2)\right)^{p/2}.
\]

**Proof.** Expand (13) in terms of the complex-conjugate, and then, under the assumption that the phase distribution of the sum term is zero-mean symmetric, all terms involving odd-order moments of \( S_2 \) will be equal to zero, and thus are not needed. Finally, we substitute the moments of Nakagami RVs.

After scaling with \( P_2 \), the UE2 receive power follows the distribution

\[ Z_2P_2^{\text{approx}} \sim \Gamma(k_2, P_2 \theta_2), \]

where \( k_2 \) and \( \theta_2 \) are the Gamma parameters matched to the moments in Lemma 5.
IV. INTERFERENCE CANCELLATION OUTAGE ANALYSIS

In the following, we calculate the outage probability for the uplink IRS-NOMA system under IC. First, we evaluate the outage probability without IC.

**Proposition 1.** Let $Z_i P_i \sim \Gamma(k_i, P_i \theta_i)$ be the received power of the $i^{th}$-UE, $Z_j P_j \sim \Gamma(k_j, P_j \theta_j)$ the received power of the $j^{th}$-UE, with $P_w$ being the noise power. The IRS-NOMA outage probability without IC is given by

$$p_{\text{out}}(i) \approx \frac{\Gamma(k_i + k_j) \Gamma(k_i + 1) \Gamma(k_j)}{(\hat{\theta}_i + k_i \hat{\theta}_j) k_i + k_j (\hat{\theta}_i)^{-k_i} - k_i} \times 2F_1 \left( 1, \hat{k}_i + \hat{k}_j; \hat{k}_i + 1; \frac{\hat{\theta}_j}{\hat{\theta}_i + \hat{\theta}_j} \right),$$

where $2F_1(\cdot;\cdot;\cdot)$ is the hypergeometric function, and

$$\hat{k}_i = k_i, \quad \hat{\theta}_i = \theta_i P_i, \quad \hat{k}_j = \frac{(k_i \theta_j P_j + P_w)^2}{k_j (\theta_j P_j)^2}, \quad \hat{\theta}_j = \frac{k_j (\theta_j P_j)^2}{k_j \theta_j P_j + P_w}.$$

**Proof.** Let $X \sim \Gamma(k_X, \theta_X)$ and $Y \sim \Gamma(k_Y, \theta_Y)$ be two Gamma RVs, then,

$$\mathbb{P}\left\{ \frac{X}{Y} \leq \epsilon \right\} = \mathbb{P}\left\{ X \leq \epsilon Y \right\} = \mathbb{E}_Y \left\{ F_X(\epsilon Y) \right\},$$

where $F_X(\cdot)$ is the CDF of $X$. After evaluating the expectation using 6.455 in [13] and some rearrangement, we arrive at

$$\mathbb{P}\left\{ \frac{X}{Y} \leq \epsilon \right\} = \frac{\Gamma(k_X + k_Y) \Gamma(k_X + 1) \Gamma(k_Y)}{(\theta_X + \epsilon \theta_Y)^{k_X + k_Y} \theta_X^{-k_X} \epsilon^{-k_X}} \times 2F_1 \left( 1, k_X + k_Y; k_X + 1; \frac{\epsilon \theta_Y}{\theta_X + \epsilon \theta_Y} \right).$$

However, the denominator in (5) is not Gamma, due to the presence of the noise term. Therefore, we approximate the interference-plus-noise term by an equivalent Gamma RV, and, via moments matching. By doing so, and using the Gamma scaling property, we are arrive at the final results.

The detection scheme we consider here is parallel, in the sense that UE1, UE2, or both can be detected correctly at the first iteration and removed from the received signal. Whatever remains can be detected in the second iteration after IC. Such formulation allows us to assume an arbitrary cancellation order and save us the hassle of ordered statistics as would be required under successive IC. This is formulated in the following proposition.

**Proposition 2.** The IRS-NOMA outage probability of the $i^{th}$-UE under IC given by

$$p_{\text{out},\text{IC}}(i) \approx 1 - \min \left( p_{\text{suc}, \text{IC}}^{(i)} + p_{\text{suc}, \text{IC}}^{(j)} p_{\text{suc}, \text{SNR}}^{(i)}, p_{\text{suc}, \text{SNR}}^{(i)} \right),$$

where $p_{\text{suc}, \text{IC}} = 1 - p_{\text{out}}$ and $p_{\text{suc}, \text{SNR}} = 1 - p_{\text{out}, \text{SNR}}$ are the success probabilities.

**Proof.** There are two paths for a successful detection of the $i^{th}$-UE: it is detected correctly in the first iteration; or, it is not, but the other UE is detected correctly, and after IC, the $i^{th}$-UE is detected interference-free in the presence of noise only. Following those events, we can approximate the success probability under IC as

$$p_{\text{suc}, \text{IC}}^{(i)} \approx p_{\text{suc}}^{(i)} + p_{\text{suc}}^{(j)} p_{\text{suc}, \text{SNR}}^{(i)}.$$

The detection sequence mentioned before is not of fully independent events; hence, the approximation sign. To further improve the approximation, we use the fact that the performance cannot be better than that of the interference-free noise-only case. We get the final results by taking the minimum between this expression and the noise-only case.

V. ANALYSIS OF AN EXAMPLE SCENARIO

We assume a scenario where UE1 is received at the BS with 10 dB higher power than UE2 through the direct links, and they are assisted by a 32-elements IRS. The strong user (UE1) and the IRS are assumed to have good LOS to the BS, while the weak user (UE2) experiences close to Rayleigh fading. The two UEs are assumed to have a moderate LOS to the IRS. This is set by adjusting the corresponding $m$ parameters. Moreover, we assume both users are transmitting with the same power, i.e., $P_1 = P_2 = P$. The pathlosses and the other scenario parameters are summarized in Table I.

| Parameter          | Value               |
|--------------------|---------------------|
| #IRS elements      | $N = 32$            |
| Transmit powers    | $P_1 = P_2 = P = 20$ dBm or $35$ dBm |
| Nakagami parameters| $m_{BS} = 6$        |
|                    | $m_{h_1} = 4$, $m_{h_2} = 1.1$ |
| Pathlosses         | $\ell_{BS} = -10$ dB |
|                    | $\ell_{h_1} = -10$ dB, $\ell_{h_2} = -20$ dB |
| Noise power        | $P_w = 0$ dBm       |

TABLE I: Scenario parameters.
In this letter, we investigated the outage performance of an IRS-assisted NOMA uplink, where all users have direct and reflection links, and all links undergo Nakagami-$m$ fading. Using second-order moments matching, the received powers of the NOMA users are approximated with Gamma RVs. This allows for flexible modeling of the propagation environment, while giving rise to tractable outage expressions under IC. We analyzed an example scenario in which one of the UEs has a dominant LOS connection to the BS, while the other UE has a dominant NLOS, and made the following observations:

- Presence of the IRS always improves the performance of the NLOS UE, irrespectively of the IRS configuration.
- At low outage thresholds, the presence of the IRS might degrade the performance of the LOS-dominated UE, if the IRS is configured to boost the other UE. This is especially pronounced at low SNR.

The accuracy of the analysis is verified by simulations.

VI. CONCLUSIONS

Final remarks: the expressions described in this paper contain division between Gamma functions. This can be problematic stability-wise when implemented. We suggest performing the calculations in the log-domain using the log $\Gamma(\cdot)$ function.

Research reproducibility: the code for generating the results in this paper can be downloaded here *TBD*.

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