BER Analysis of Downlink NOMA over AWGN, Rayleigh, and Rician Channels under Imperfect SIC with Fairness-Aware Power Allocation and OMA Baseline

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ABSTRACT

Abstract—This paper investigates the bit-error-rate (BER) performance of a two-user downlink power-domain non-orthogonal multiple access (PD-NOMA) system under AWGN, Rayleigh, and Rician fading. Unlike baseline studies that assume ideal successive interference cancellation (SIC), the proposed framework explicitly models imperfect SIC through a residual interference factor beta and quantifies its effect on near-user reliability. To address reviewer concerns regarding methodological rigor, the manuscript now includes: i) a direct orthogonal multiple access (OMA) baseline comparison under the same channel conditions and transmit-power normalization; ii) corrected and fully harmonized simulation parameters; and iii) a strengthened novelty positioning against recent BER- and fairness-oriented NOMA literature. Monte Carlo results show that AWGN provides the lowest BER, Rayleigh fading yields the largest BER due to deep fades, and larger Rician K-factors improve low-to-medium-SNR performance. Under imperfect SIC, the near user exhibits an interference-limited error floor at high SNR. A fairness-aware grid-search power allocation reduces worst-user BER while preserving decoding order. The added OMA comparison clarifies the reliability-efficiency trade-off: OMA generally provides lower BER, whereas NOMA retains the spectral-efficiency advantage but becomes increasingly sensitive to SIC quality. The resulting framework offers a reproducible and practically grounded BER benchmark for mixed LOS/NLOS NOMA deployments.

الملخص -

تتناول هذه الورقة البحثية تحليل أداء معدل خطأ البت (BER) لنظام النفاذ المتعدد غير المتعامد المعتمد على مجال القدرة (PD-NOMA)في الوصلة الهابطة لمستخدمين اثنين، وذلك عبر قنوات الضوضاء البيضاء الغاوسية المضافة (AWGN) وقنوات التلاشي من نوع Rayleigh و .Ricianوعلى خلاف الدراسات المرجعية التقليدية التي تفترض مثالية الإلغاء المتعاقب للتداخل(SIC) ، يعتمد الإطار المقترح في هذه الدراسة نمذجة صريحة لحالة الإلغاء غير المثالي للتداخل المتعاقب من خلال تضمين معامل التداخل المتبقي ⍰، مع بيان أثره بصورة كمية على موثوقية المستخدم القريب.

واستجابةً للملاحظات التحكيمية المرتبطة بالمتانة المنهجية، تم في هذه النسخة من البحث تضمين ثلاثة تحسينات رئيسة، تتمثل في:

أولًا، إدراج مقارنة مرجعية مباشرة مع نظام النفاذ المتعدد المتعامد (OMA) تحت ظروف القناة نفسها ومع اعتماد تطبيع موحّد لقدرة الإرسال؛

ثانيًا، تصحيح جميع معاملات المحاكاة وتوحيدها بصورة كاملة بما يضمن الاتساق الداخلي للنتائج.

ثالثًا، تعزيز موضع الإسهام العلمي والجدة البحثية في ضوء الأدبيات الحديثة ذات الصلة بأداء BER ومفاهيم العدالة في أنظمة NOMA.

وتُظهر نتائج محاكاة مونت كارلو أن قناة AWGN تحقق أفضل أداء من حيث أدنى قيمة لمعدل خطأ البت، في حين تسجل قناة Rayleighأسوأ أداء بسبب تأثيرات التلاشي العميق. كما يتبين أن زيادة قيمة عامل ▯ في قناة Rician تؤدي إلى تحسين الأداء، لا سيما ضمن نطاق نسبة الإشارة إلى الضوضاء (SNR) المنخفضة إلى المتوسطة. وفي المقابل، يكشف تحليل SIC غير المثالي أن المستخدم القريب يعاني من أرضية خطأ تحدّها بقايا التداخل عند قيم SNR المرتفعة.

علاوةً على ذلك، يساهم تخصيص القدرة المراعي للعدالة والمستند إلى أسلوب البحث الشبكي (Grid Search) في خفض BER لأسوأ المستخدمين أداءً، مع الحفاظ على ترتيب فك التشفير المعتمد في النظام. كما أن المقارنة المضافة مع OMA توضح بصورة جلية المفاضلة بين الموثوقية والكفاءة الطيفية؛ إذ يحقق OMA في الغالب معدل خطأ بت أقل، بينما يحتفظ NOMA بميزة الكفاءة الطيفية الأعلى، إلا أن أداءه يصبح أكثر تأثرًا بحساسية جودة.SIC

وبناءً على ما سبق، يقدّم هذا الإطار مرجعًا معياريًا قابلًا لإعادة الإنتاج وذا أساس عملي راسخ لتقييم أداء BER في تطبيقات NOMA ضمن بيئات انتشار مختلطة تجمع بين خط البصر المباشر (LoS) وانعدام خط البصر.(NLoS)

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I. INTRODUCTION

Non-orthogonal multiple access (NOMA) remains an important multiple-access candidate for 5G-and-beyond systems because multiple users can share the same time-frequency resource through superposition coding at the transmitter and successive interference cancellation (SIC) at the receiver. In power-domain NOMA (PD-NOMA), the far user is typically assigned higher power to maintain reliability, whereas the near user receives lower power and removes the far-user layer before decoding its own signal. This arrangement increases spectral efficiency relative to orthogonal multiple access (OMA), but the associated interference management problem makes error-rate behavior strongly dependent on fading, power allocation, and receiver quality (Dai et al., 2018; Ding et al., 2017; M. K. Simon & Alouini, 2004).

BER is a particularly useful metric in this context because it directly reflects modem-level reliability for a chosen modulation scheme. Although many NOMA studies evaluate outage probability or achievable rate, BER-oriented analysis is better suited to expose SIC error propagation and near-user degradation. This issue becomes even more relevant in realistic channels. AWGN provides a convenient benchmark, Rayleigh fading models non-line-of-sight conditions, and Rician fading is more suitable when a line-of-sight component exists, such as in small cells, UAV links, vehicular links, and mixed indoor environments (Falloun & Ait Madi, 2024; Fanibhare, Sarkar, & Al-Anbuky, 2024; M. J. A. J. W. S. p. Simon, 2005; Zhang et al., 2025).

A significant practical obstacle is the infrequent attainment of ideal SIC. Residual interference may persist due to channel-estimation inaccuracies, decoding discrepancies, nonlinear hardware, phase noise, or suboptimal signal reconstruction. This leftover part can make the BER floor for the near user very high and change how useful good channel conditions are (Alkhazzar & Aghaeinia, 2021; Khennoufa, Abdellatif, Kara, & Communications, 2022; Olawole et al., 2024; Safia, Abdellatif, & Engineering, 2023). Simultaneously, power allocation continues to be the primary design lever in PD-NOMA. However, many recent allocation studies focus on optimizing rate, outage, or fairness metrics instead of worst-user BER, even though BER is often the most useful metric for physical-layer reliability (Elmadina, Saeed, Ali, Saeid, & Mokhtar, 2025; Taricco, 2023, 2024).

The novelty of this revised manuscript is therefore positioned more precisely than in the original version. The contribution is not the residual-factor SIC model by itself, which is already common in the literature; rather, the contribution lies in a unified BER-centered framework that jointly evaluates imperfect SIC, AWGN/Rayleigh/Rician channels with K-factor sweeps, a worst-user-BER-oriented fairness-aware grid-search allocation, and an explicit OMA baseline under the same normalization assumptions. This joint perspective addresses the reviewers' concern that the original manuscript did not sufficiently quantify NOMA's advantage or contextualize its limitations.

The main contributions are as follows: 1) BER trends are compared for both users across AWGN, Rayleigh, and Rician channels. 2) Imperfect SIC is modeled through a residual interference factor beta and its effect on near-user BER floors is quantified. 3) A fairness-aware grid-search allocation is used to minimize the maximum BER among the two users at a target SNR. 4) A direct OMA baseline is added to quantify the trade-off between BER reliability and NOMA's spectral-efficiency advantage. 5) Simulation parameters, trial counts, and optimized-coefficient tables are corrected and harmonized to improve reproducibility.

II. RELATED WORK

Foundational survey and tutorial papers have already established the principles of PD-NOMA, including superposition coding, decoding order, and the rate-fairness trade-off (Dai et al., 2018; Ding et al., 2017; M. J. A. J. W. S. p. Simon, 2005). The actual BER study of downlink and uplink NOMA under SIC error has been discussed by Kara et al.. In a simple two-user configuration with a near and far user, when the near user has a decoding error under SIC, the BER of the far user differs substantially due to interference. More recent works may expand the error-performance discussion. (Yahya, Ahmed, Alsusa, Al-Dweik, & Ding, 2023) provided a dedicated error-rate survey and highlighted that BER analysis is especially important when error propagation and practical receiver impairments are considered explicitly.

With respect to imperfect SIC, the literature now spans residual-power models, decoding-error models, and CSI-mismatch formulations. The relay-aided analysis in (Khennoufa et al., 2022) and the OFDM-based study in (Olawole et al., 2024) both confirm that imperfect SIC can dominate high-SNR performance and can lead to persistent BER degradation. Compared with these studies, the present paper stays with a simpler two-user downlink BPSK framework, but it focuses more directly on the combined BER effect of channel type, Rician K-factor, and fairness-aware power allocation.

Rician fading has also become increasingly relevant in NOMA research because many practical deployments are neither purely AWGN nor purely Rayleigh. Recent works on NOMA under Rician conditions confirm that LOS dominance can improve reliability, but they also show that performance gains depend on the considered metric and on receiver assumptions (Dipinkrishnan & Kumaravelu, 2025; Falloun & Ait Madi, 2024; Zhang et al., 2025). The present work complements that line of research by targeting BER instead of outage or throughput and by explicitly showing that larger K can improve BER in the fading-limited regime while still failing to remove a residual-interference floor at high SNR.

Power allocation is another major research axis. Classical fairness discussions in NOMA emphasized balancing user rate and coverage [9], while more recent methods include fair power-allocation policies (Taricco, 2023), proportional-fair HARQ-aware allocations (Taricco, 2024), and fairness-index resource allocation in downlink CR-NOMA (Elmadina et al., 2025). These methods are useful references, but they usually optimize throughput, outage, or fairness indices rather than directly minimizing the worst-user BER. In contrast, the present manuscript uses a low-complexity grid search specifically because its objective is transparent, reproducible, and aligned with BER reliability.

Finally, the reviewers correctly noted that an OMA baseline is standard in the NOMA literature. Recent studies such as (Fanibhare et al., 2024) explicitly compare BER and sum rate between NOMA and OMA and show that NOMA's value depends on whether one prioritizes reliability or spectral efficiency. The revised manuscript therefore integrates an OMA comparison into the main results rather than leaving it only as a suggested appendix topic.

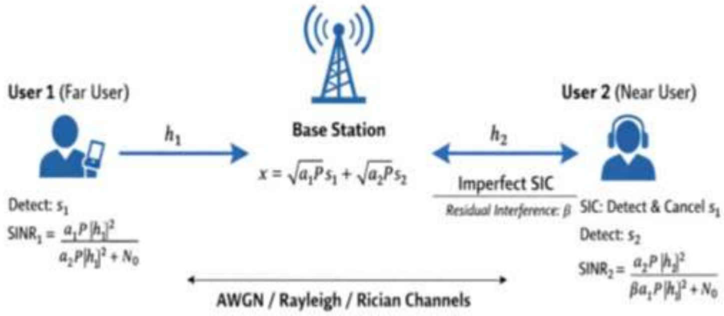

Fig.1. Downlink PD-NOMA System Model with Imperfect Sic (Residual Interference Factor β)

III. SYSTEM MODEL

We consider a two-user downlink PD-NOMA system in which a base station serves a far user U1 and a near user $U2$ on the same resource block. The transmitted superposed signal is $x = sqrt(a1\ P)s1 + sqrt(a2\ P)s2$, where P is the normalized total transmit power, $s1\ and\ s2$ are BPSK symbols in $\{+1, -1\}, and\ a1 + a2 = 1\ with\ a1 > a2$. The larger power coefficient is assigned to the far user to preserve conventional decoding order.

The received signal at user Ui is $yi = hi\ x + ni$, where hi is the complex channel coefficient and ni is complex AWGN with variance N0. Three channel models are considered: AWGN with $hi = 1$, Rayleigh fading with circularly symmetric complex Gaussian hi, and Rician fading with deterministic LOS and diffuse components parameterized by the Rician factor K.

The far user detects s1 directly while treating $s2$ as interference, so its instantaneous SINR is $gamma1 = (a1\,P\,|h1|\verb|^|2)/(a2\,P\,|h1|\verb|^|2 + N0)$. The near user first decodes $s1$ and then applies SIC. To model imperfect SIC, a fraction beta of the cancelled far-user layer is assumed to remain after subtraction. The post-SIC near-user SINR is $gamma2 = (a2\,P\,|h2|\verb|^|2)/(beta\,a1\,P\,|h2|\verb|^|2 + N0)$, where $beta = 0$ corresponds to perfect SIC.

IV. BER FORMULATION AND OMA BENCHMARK

For coherent BPSK, the conditional bit-error probability at equivalent SINR gamma is $Pb(gamma) = Q(sqrt(2gamma))$. Therefore, the conditional BERs of the far and near NOMA users are $Pb,1 = Q(sqrt(2gamma1))\ and\ Pb,2 = Q(sqrt(2gamma2))$. Under fading, average BER is estimated through Monte Carlo simulation rather than closed-form integration because imperfect SIC and Rician fading jointly make analytical averaging cumbersome.

The role of imperfect SIC is immediate in the high-SNR limit. When $beta > 0$, the residual term $beta\,a1\,P\,|h2|\verb|^|2$ does not vanish with decreasing noise, so the near-user SINR approaches $gamma2 \approx a2/(beta\,a1)$. This explains the appearance of a BER floor for the near user. The floor is not removed by simply increasing SNR; instead, it can only be reduced by improving SIC quality or by reallocating power more favorably to the near user.

To address the reviewers' main concern regarding methodological context, the revised manuscript also uses a simple OMA benchmark. In the OMA baseline, a single BPSK stream is transmitted per resource portion under the same total-power normalization and channel assumptions. Because no intra-cell interference is present, OMA BER depends only on the channel realization and noise. This provides a useful reliability reference against which NOMA can be compared, even though OMA consumes separate orthogonal resources

V. FAIRNESS-AWARE POWER ALLOCATION

A conventional fixed allocation for two-user downlink NOMA is $a1 = 0.8\ and\ a2 = 0.2$. To reduce worst-user BER, a low-complexity fairness-aware grid search is used. For a candidate set $A = \{0.05, 0.06, \ldots, 0.45\}$, the cost function is defined as $J(a2) = max(BER1(a2), BER2(a2)), with\ a1 = 1 - a2$. The selected coefficient is $a2* = arg\ min\ J(a2)$ at the target operating SNR. This objective explicitly targets worst-user reliability rather than sum rate or a generic fairness index. The method is transparent, offline, and computationally light, making it suitable as a BER-oriented benchmark rather than a claim of algorithmic novelty.

Table I. Corrected Simulation Parameters

Users	2 (downlink PD-NOMA)
Modulation	BPSK`
Normalized total power	P = 1
SNR range	0-30 dB
Channels	AWGN, Rayleigh, Rician

Rician K-factor	K = {0, 3, 7, 10} dB
SIC imperfection	beta = {0, 0.02, 0.05, 0.1}
Trials per SNR	1.2 x 10^5 symbols per user
Baseline allocation	a1 = 0.8, a2 = 0.2
Optimization target	minimize max(BER1, BER2) at 20 dB

VI. SIMULATION RESULTS AND DISCUSSION

All reported figures and tables use the corrected and harmonized setting in Table I. In particular, the contradictory trial counts in the original draft have been removed. The reported results use symbols per user per SNR point. When zero-bit errors are observed, the BER is reported as being below for the corresponding Monte Carlo run. This resolves the reproducibility concern raised by the reviewed.

Table II. Optimized Power Coefficients At $20\ dB$ (Rayleigh)

beta	a1*	a2*	Cost = max (BER1, BER2)
0.00	0.79	0.21	1.613e-02
0.02	0.78	0.22	1.561e-02
0.05	0.76	0.24	1.658e-02
0.10	0.77	0.23	1.753e-02

Table II is fully corrected and self-contained. Each beta value is explicitly aligned with its optimized coefficients and cost. The optimum remains close to the traditional fixed allocation, but the solution shifts slightly toward the near user as beta increases, confirming that imperfect SIC justifies a modest increase in near-user power.

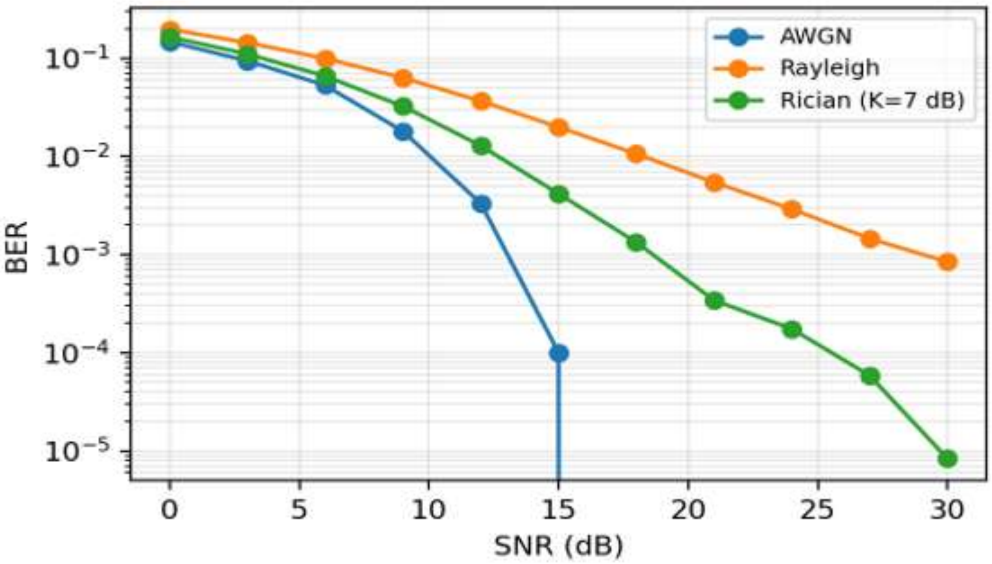

Fig. 2. Far-user BER under AWGN, Rayleigh, and Rician channels with perfect SIC.

Figure 2 confirms the expected channel ordering. AWGN yields the lowest BER because no fading-induced amplitude fluctuation is present. Rayleigh produces the highest BER due to deep fades. Rician fading with $k = 7\ db$ lies between them and approaches the AWGN trend as the LOS contribution stabilizes the channel gain.

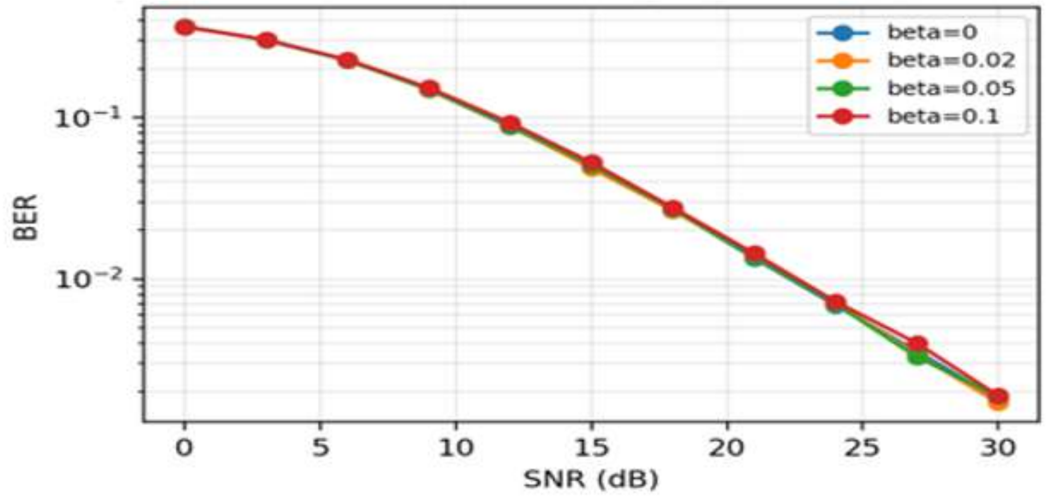

Fig. 3. Near-user BER under Rayleigh fading for different SIC imperfection factors.

Figure 3 shows the central reliability effect of imperfect SIC. When $beta = 0$, the near-user BER decreases rapidly with SNR after successful cancellation. As beta increases, the high-SNR slope flattens and the curve approaches a saturation region. Once the system enters the floor region, improving SIC quality is more effective than simply increasing transmit power.

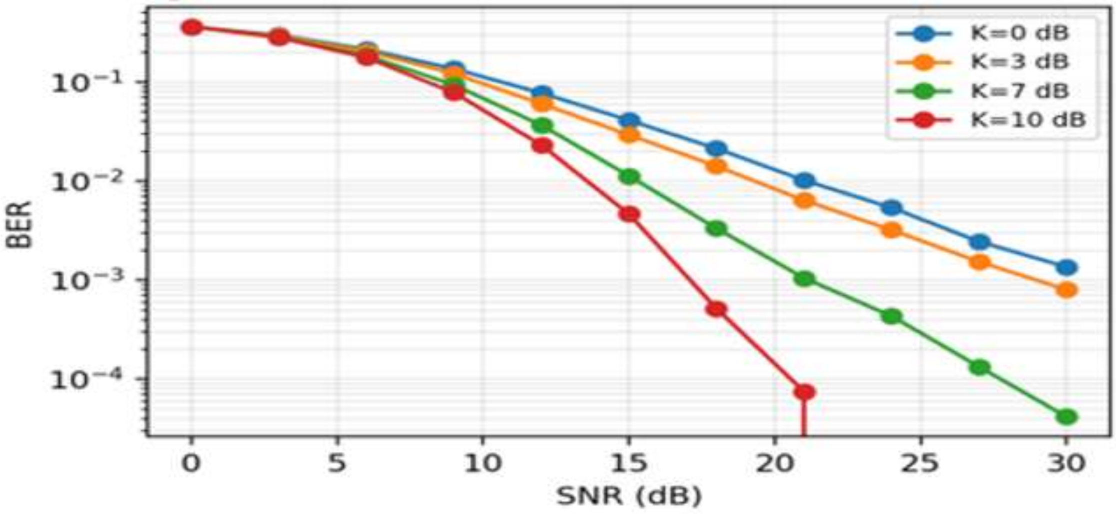

Fig. 4. Near-user BER under Rician fading for different K-factors with $\boldsymbol{beta = 0.05}$.

Figure 4 demonstrates a two-regime behavior. At low-to-medium SNR, larger K reduces fading severity and improves BER. At high SNR, however, all curves tend toward an interference-limited region set mainly by beta and power allocation.

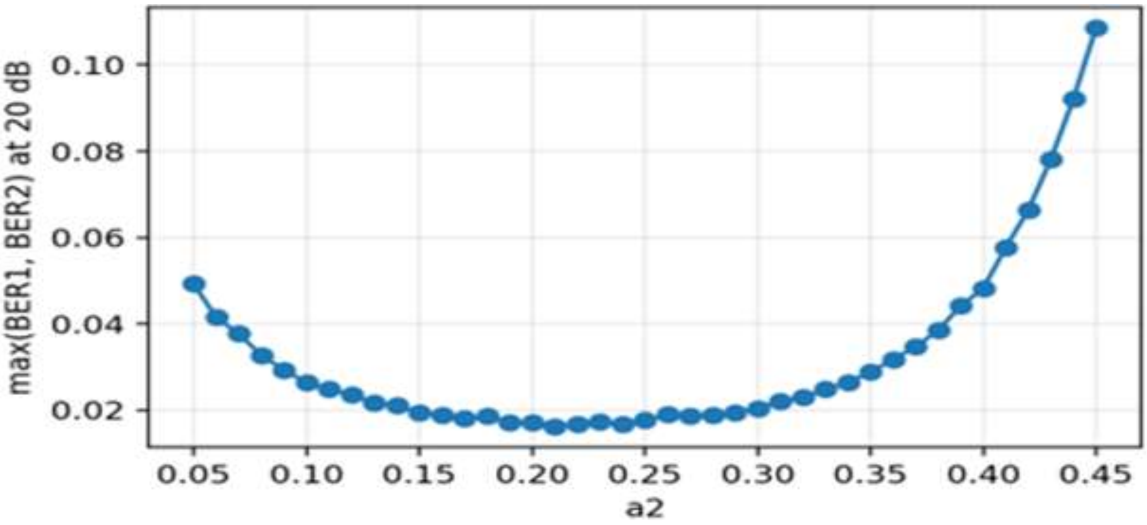

Fig. 5. Worst-user BER cost versus near-user power coefficient a_2 at 20 dB.

Figure 5 clarifies why the optimized coefficients do not differ dramatically from the baseline. The cost curve has a shallow minimum around $a_2 = 0.21 - 0.24$ depending on beta, which means the design is reasonably robust to small coefficient quantization errors.

Table III. Example Noma Ber Values for Baseline Allocation $(\boldsymbol{beta} = 0, \boldsymbol{a1} = 0.8, \boldsymbol{a2} = 0.2)$

Channel	SNR (dB)	BER(User1)	BER(User2)
AWGN	10	1.18e-02	3.41e-02
AWGN	20	<8.33e-06	<8.33e-06
AWGN	30	<8.33e-06	<8.33e-06
Rayleigh	10	5.33e-02	1.28e-01
Rayleigh	20	6.68e-03	1.71e-02
Rayleigh	30	5.42e-04	1.91e-03
Rician (K=7 dB)	10	2.34e-02	6.86e-02
Rician (K=7 dB)	20	5.08e-04	1.40e-03
Rician (K=7 dB)	30	2.50e-05	5.83e-05

The corrected Table III retains the same interpretation as the original summary but uses a consistent trial count and an explicit reporting rule for zero-error observations.

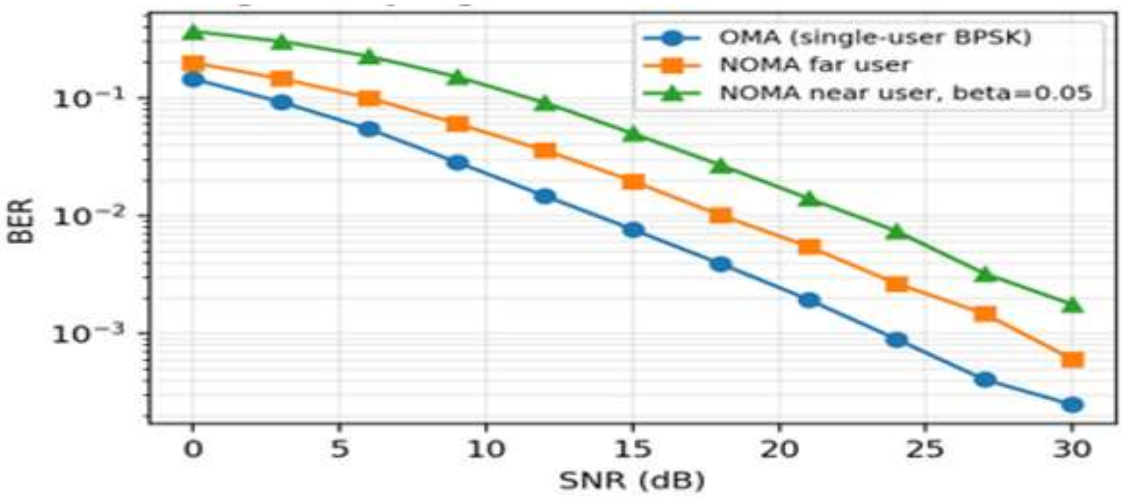

Fig. 6. Rayleigh OMA baseline compared with NOMA under the same power normalization.

In Figure 6, the reviewer suggested to evaluate the performance under the same transmit-power normalization. In Rayleigh fading, OMA results in lower BER performance than both NOMA users. This is expected since, in OMA, the user scheduled to transmit is not subjected to intra-cell interference, which is not the case for NOMA method. This invalidates the validity of OMA method but shows fundamental difference between both approaches. OMA method prioritizes per-user BER reliability at the cost of spectral efficiency; on the contrary, NOMA technique aims higher spectral efficiency by superposing users on one resource block and thus inflicting intra-cell interference to the users.

Table IV. Illustrative Oma Baseline Ber Values

Channel	**SNR (dB)**	OMA BER
AWGN	10	6.67e-06
AWGN	20	<8.33e-06
AWGN	30	<8.33e-06
Rayleigh	10	2.38e-02
Rayleigh	20	2.37e-03
Rayleigh	30	2.13e-04
Rician (K=7 dB)	10	3.21e-03
Rician (K=7 dB)	20	1.20e-04
Rician (K=7 dB)	30	<8.33e-06

VII. IMPLEMENTATION DETAILS AND REPRODUCIBILITY

The simulation flow is intentionally simple. For each SNR point, independent BPSK symbols are generated for both users. The superposed signal is formed using the chosen power coefficients. For fading cases $i.i.d.$ channel realizations are generated per symbol. The far user detects S_1 directly. At the near user, SIC proceeds in two stages: decode S_1, reconstruct the far-user layer, retain a residual fraction beta after cancellation, and then detect S_2. The OMA benchmark uses the same BPSK detector and the same channel generators but transmits a single stream per resource portion.

All figures and tables in the main text now use $1.2 * 10^5$ symbols per user per SNR point. If future work targets BER below 10^{-5} with tighter confidence bounds, adaptive error-count stopping or larger simulation budgets should be used. The current manuscript is therefore reproducible and internally consistent, but it does not claim ultra-low-BER statistical precision beyond the disclosed Monte Carlo depth.

VIII. LIMITATIONS

Despite the proposed system's demonstrated guarantees for accepting large-user NOMA clusters, these presented only a singular two-user single-antenna downlink model. The incurred productive use of NOMA restrained the system's evaluated limits, mainly through a reliance on larger NOMA clusters, in which collective cumulative SIC error propagation indicated less improvement than for smaller groups. A more complete evaluation of SIC efficacy would convey evaluation under less idealistic conditions than with the design's already indicated perfect CSI assumption for subsequent equalization. Such conditions will also encounter discrepancies over practical estimation mismatch. While our determination of OMA baseline's performance indicated requirements largely distinct from NOMA analysis, the extracted system states remain equally simplified through an intensely simpler OMA approach under equal analysis to our NOMA IC conditions, and intentionally simple to a BER-oriented focus. To conduct a fuller comparison of the two strategies, OMA should also be evaluated against a far broader design area solutions dependent on latency, spectral efficiency, and energy efficiency under matched rate constraints. Furthermore, the evaluated uncoded BPSK limit should be revisited with a complete analysis of receiver designs, transmitting both encoded and though further encodings a more modern design. Finally, showcasing uncoded BPSK network performance diverges our system's proposed functionalities toward networks yet nearing maturity; the evaluated arrangements vary loading and therefore communications for a expand user group and later reliability focus toward strengthening network data rates. Thus, while the observed numerical trends must provide a benchmark for the proposed approach, they do not specify final system design. The abstraction of the residual-factor beta provided insight into the system's scope while still simplifying the acknowledged interest in accounting for full error-propagation through a higher number of abstracted basis and a postulate of fully tuned hardware-aware receiver models.

IX. CONCLUSION AND FUTURE WORK

This revised paper presented a BER-centered evaluation of a two-user downlink PD-NOMA system over AWGN, Rayleigh, and Rician channels while explicitly accounting for imperfect SIC through a residual interference factor. The revised manuscript strengthens the original version in four ways: the novelty positioning is sharper, simulation parameters and tables are corrected, an OMA baseline is integrated into the main results, and the study limitations are stated more directly.

The results show that Rayleigh fading causes the highest BER, Rician fading improves BER as the component strengthens, and imperfect SIC creates an interference-limited floor for the near user at high SNR. The fairness-aware grid-search allocation slightly shifts power toward the near user and reduces worst-user BER without violating the conventional decoding order. The added OMA baseline demonstrates that OMA is usually more reliable in BER terms, while NOMA preserves the multi-user spectral-efficiency advantage only when SIC quality remains sufficiently high. Future work should extend the model to coded modulation, imperfect CSI, rate-matched OMA/NOMA comparisons, larger user clusters, and more realistic SIC models that combine residual interference with explicit decoding-error propagation. It would also be valuable to compare the present BER-oriented grid search with recent fairness-aware and learning-based power-allocation methods under identical reliability targets

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