

# Impact of Inter-Hop Correlation on Reconfigurable Intelligent Surfaces

Gregory Anzilio, Eduardo Nunes Velloso, and José Cândido Silveira Santos Filho

**Abstract**—Reconfigurable Intelligent Surfaces (RISs) are commonly analyzed under the assumption that the base-station–RIS and RIS–user-equipment hops are statistically independent. This assumption can be inaccurate when the two hops interact with common scatterers or clusters, producing inter-hop correlation in the RIS-side angular support. This paper investigates the impact of such inter-hop power correlation on a phase-optimized RIS-assisted single-input–single-output channel. We propose a geometry-based shared-scatterer model in which the two hops have common scatterer angles and power weights, while the small-scale fading amplitudes are correlated through a tunable parameter. The results show that inter-hop correlation increases the average phase-aligned cascaded gain but can degrade outage performance by increasing the probability of jointly weak cascaded channel realizations. These results indicate that independent-hop models may overestimate RIS reliability, even when average gain predictions appear favorable.

**Keywords**—reconfigurable intelligent surfaces, geometry-based channel modeling, inter-hop correlation, spatial correlation.

## I. INTRODUCTION

Reconfigurable Intelligent Surfaces (RISs) consist of a series of passive elements, called meta-atoms, that can individually control the phase of reflection of an incident electromagnetic wave, thereby redirecting it. In this manner, a RIS can be used to improve existing channel conditions [1]. Despite the advantages of RIS-assisted systems, several technical challenges remain, such as phase-shift optimization, channel estimation algorithms, and RIS positioning and orientation [2], all of which require realistic channel models. To this end, Geometry-Based Stochastic Models (GBSMs) have been traditionally applied in wireless communications due to their ability to generate complex mathematical properties while maintaining geometric intuition and mathematical tractability. They combine the practicality of analytical models and maintain the physical intuition behind geometric models [3].

Currently, most RIS models assume independent channels between RIS elements. Despite this, it has been shown in [4] that, even in isotropic conditions, a simple extension of Clarke’s model reveals inter-element correlation (henceforth called spatial correlation) in planar RISs. This model can be easily extended into a Rice channel scenario, as seen in [5] and [6], and has been explored in estimation algorithms [7]. GBSM

models with different geometries have been presented in [8]–[11] to be used in multiple-input multiple-output (MIMO), including multiuser MIMO (MU-MIMO) and point-to-point MIMO with RISs.

A related phenomenon in systems with multiple links is *inter-link* correlation, which may persist even when there is significant spatial separation between channel links, especially in indoor spaces [12]. This effect arises from dominant multipath components (MPCs), which contain most of the channel power that may be shared between links. This implies that there is some sort of angular correlation between the received power of different links manifesting as correlated angle power profiles. These dominant MPCs can be either on the receiver or transmitter side and can be modeled in GBSM using the concept of shared scatterers [13], [14], where a scatterer appears with a correspondent between different channel links.

In this paper, a *link* denotes the end-to-end base-station (BS)–user-equipment (UE) communication channel, whereas a *hop* denotes one segment of the RIS-assisted reflected path. Multiple user (inter-link) correlation has been modeled analytically in RIS systems by [7] due to unfavorable propagation conditions. Understanding this effect is therefore important for selecting RIS channel models and interpreting performance predictions. However, little has been done to analyze the effects of inter-hop correlation in the cascaded RIS channel.

This lack of effort is compounded by the difficulty of obtaining measurements to validate RIS models against. RIS inter-hop correlation is also particularly difficult to measure, as RISs lack radio-frequency chains necessary for measurements. Because of this, the scale of the phenomenon remains unknown. We can still use measurements conducted in other situations, such as MU-MIMO in indoor spaces [15], which indicate that inter-hop correlation may be significant. GBSMs are widely used to model inter-link correlation, and they clearly justify modeling decisions that create correlation with physical intuition. Thus, we believe that these models can be adapted to account for inter-hop correlation as well.

In certain environments, objects positioned near the RIS affect the propagation of both the BS–RIS and RIS–UE hops. Such shared scatterers induce similar RIS-side angular power profiles, ultimately leading to power correlation between those hops. In this paper, we study inter-hop power correlation in a RIS-assisted single-input single-output (SISO) channel. These are our main contributions: (i) a geometry-based shared-scatterer model with common scatterer angles and power weights, and tunable correlation between corresponding small-scale fading powers; (ii) closed-form expressions for the intra-hop spatial correlation and inter-hop power correlation; (iii)

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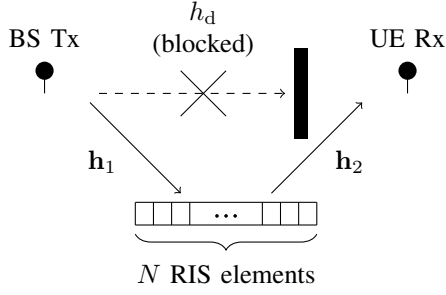


Fig. 1: Typical RIS-assisted SISO system, with a linear uniformly distributed RIS with  $N$  elements. The channels  $\mathbf{h}_1$  and  $\mathbf{h}_2$  represent the BS-RIS and RIS-UE hops, respectively, while  $h_d$  represents the blocked direct BS-UE channel.

an analysis, supported by Monte Carlo simulations, showing that inter-hop correlation can increase average phase-aligned cascaded gain while worsening outage behavior.

*Notation.* Throughout the paper, boldface symbols denote vectors;  $\mathcal{N}(0, 1)$  and  $\mathcal{CN}(0, 1)$ , the standard and circularly symmetric Gaussian distributions;  $\mathcal{U}(a, b)$ , the uniform distribution in  $[a, b]$ ;  $\text{Ray}(\sigma)$ , the Rayleigh distribution with scale parameter  $\sigma$ ;  $\mathbb{E}[\cdot]$ , expectation;  $\text{Corr}(\cdot, \cdot)$ , correlation; the superscripts  $(\cdot)^T$  and  $(\cdot)^*$ , the transpose and the complex conjugate operations, respectively.

## II. SYSTEM AND CHANNEL MODELS

### A. RIS-Assisted Channel Model

Consider a SISO channel aided by a RIS array with  $N$  elements, as in Fig. 1. The received signal is

$$y = h_{\text{eff}}x + w, \quad (1)$$

where  $x$  is the transmitted signal,  $w$  is additive noise, and  $h_{\text{eff}}$  is the total effective channel.

The effective channel is composed of a direct path  $h_d$  and a path that goes through the RIS:  $h_{\text{eff}} = h_d + h_{\text{RIS}}$ . To focus on the reflected RIS-assisted path, we will be assuming the direct link is blocked and set  $h_d = 0$ , so  $h_{\text{eff}} = h_{\text{RIS}}$ .

This cascaded channel is thus the composition of the  $\mathbf{h}_1^T$  single-input multiple-output (SIMO) BS-RIS hop, the  $\mathbf{h}_2$  multiple-input single-output (MISO) RIS-UE hop, and the RIS phase shift matrix  $\mathbf{\Theta}$ , such that

$$h_{\text{RIS}} = \mathbf{h}_1^T \mathbf{\Theta} \mathbf{h}_2. \quad (2)$$

The phase shift matrix  $\mathbf{\Theta}$  is a diagonal matrix with elements  $e^{-j\vartheta_n}$ ,  $n = 1, \dots, N$ , representing the phase shifts for each array element.

In an optimized RIS with perfect channel state information, the set of phase shifts  $\{\vartheta_n\}$  is chosen for perfect phase compensation, i.e.,  $\vartheta_n = \arg(h_{1,n}h_{2,n})$ , which is the choice that maximizes the effective channel:

$$h = \max_{\mathbf{\Theta}} |h_{\text{RIS}}| = \max_{\mathbf{\Theta}} |\mathbf{h}_1^T \mathbf{\Theta} \mathbf{h}_2| = \sum_{n=1}^N |h_{1,n}| |h_{2,n}|. \quad (3)$$

This means that the RIS-assisted channel quality depends mostly on the alignment between channel envelopes of the

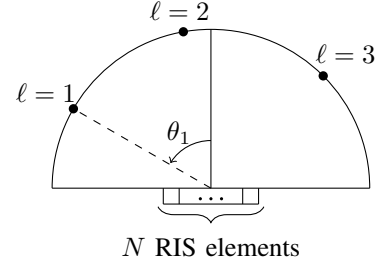


Fig. 2: GBSM model for a uniform linear RIS with  $N$  elements and  $L = 3$  scatterers. The scatterer angular coordinates are shared between the two hops and are indexed by  $\ell$ . The scatterer angular position  $\theta_1$  is shown for scatterer  $\ell = 1$ .

two cascaded hops. This phase-aligned SISO RIS model is standard in analyses of single-user RIS systems with spatially correlated fading [5], [6].

### B. Shared-Scatterer Geometry and Angular Power Profile

As in the physically motivated RIS fading models in [4], we model the RIS-side channel coefficients through array responses induced by incoming angular components. We consider a one-ring model, where the RIS is centered on a semicircle surrounded by  $L$  scatterers (Fig. 2). Each scatterer  $\ell$  is represented by a RIS-side angular coordinate  $\theta_\ell$ . For the BS-RIS hop, this angle can be interpreted as an angle of arrival at the RIS; for the RIS-UE hop, it represents the corresponding RIS-side departure/arrival coordinate under the same array-response convention. This abstraction allows both hops to share the same angular support while keeping their small-scale fading realizations distinct. The shared angular support is inspired by multi-link GBSMs, where common clusters are used to induce correlation between different links [12]–[14].

In this work, we consider a uniform linear RIS array with element spacing of half a wavelength. This means that a wave with an impinging angle  $\theta$  has a phase response given by the steering vector

$$\mathbf{a}(\theta) = [1 \quad e^{j\pi \sin \theta} \quad \dots \quad e^{j\pi(N-1) \sin \theta}]^T, \quad (4)$$

with the angle  $\theta$  measured with respect to the first array element.

For each hop  $i \in \{1, 2\}$ , we consider that the  $L$  scatterers are shared at the same angular positions  $\theta_1, \dots, \theta_L$ , and the channel with impinging waves at those angles is given by

$$\mathbf{h}_i = [\mathbf{a}(\theta_1) \quad \dots \quad \mathbf{a}(\theta_L)] \begin{bmatrix} \alpha_{i,1} e^{j\phi_{i,1}} \\ \vdots \\ \alpha_{i,L} e^{j\phi_{i,L}} \end{bmatrix}, \quad (5)$$

where  $\alpha_{i,\ell}$  and  $\phi_{i,\ell}$  are the random amplitudes and phases of each wave for each hop.

We also consider that the wave amplitudes are normalized in such a way that  $\mathbb{E}[\alpha_{i,\ell}^2] = p_\ell$ , which are the normalized average power fractions for each scatterer with the following properties:

$$p_\ell > 0, \quad \sum_{\ell} p_\ell = 1. \quad (6)$$

For simplicity, we assume uniformly distributed RIS-side angles,

$$\theta_\ell \sim \mathcal{U}(-\pi/2, \pi/2), \quad (7)$$

and log-normally distributed large-scale fading at each scatterer. To achieve the constraints of (6), this choice corresponds to logistic-normal power fractions:

$$p_\ell = \frac{e^{z_\ell}}{\sum_k e^{z_k}} \quad (8)$$

with  $z_\ell \sim \mathcal{N}(0, 1)$ .

### C. Inter-Hop Correlated Small-Scale Fading

While the large-scale effects of  $\mathbf{p} = \{p_\ell\}_{\ell=1}^L$  and  $\boldsymbol{\theta} = \{\theta_\ell\}_{\ell=1}^L$  are shared for both hops, the  $\boldsymbol{\alpha}_i = \{\alpha_{i,\ell}\}_{\ell=1}^L$  and  $\boldsymbol{\phi}_i = \{\phi_{i,\ell}\}_{\ell=1}^L$  that define the multipath fading model are hop-specific.

The stochastic model for the amplitude of wave  $\ell$  in hop  $i$  is given by  $\alpha_{i,\ell} = \sqrt{p_\ell} r_{i,\ell}$ , with

$$r_{1,\ell}, r_{2,\ell} \sim \text{Ray}\left(1/\sqrt{2}\right) \quad (9)$$

to ensure the normalization factor  $\mathbb{E}[r_{i,\ell}^2] = 1$ , and with the inter-hop correlation

$$\text{Corr}(r_{1,\ell}^2, r_{2,\ell}^2) = \rho^2 \quad (10)$$

representing the effect of sharing common clusters of scatterers between hops. To generate those correlated Rayleigh amplitudes, we first draw correlated complex Gaussian variables with correlation coefficient  $\rho$  and then set  $r_{i,\ell}$  to their amplitudes.

We also consider that the phase of each scatterer is uniformly distributed and independent across all hops and waves:

$$\phi_{i,\ell} \sim \mathcal{U}(-\pi, \pi). \quad (11)$$

Thus, the model introduces correlation between the scatterer powers of the two hops, but no deterministic phase coherence.

## III. THEORETICAL ANALYSIS

Under this geometry-based model, the marginal distribution of each  $h_{i,n}$  can be promptly determined by observing that

$$h_{i,n} = \sum_{\ell=1}^L \sqrt{p_\ell} e^{j\pi(n-1)\sin\theta_\ell} r_{i,\ell} e^{j\phi_{i,\ell}} \quad (12)$$

is a linear combination of independent complex Gaussian random variables, which is also complex Gaussian with variances adding in quadrature:

$$h_{i,n} | \mathbf{p}, \boldsymbol{\theta} \sim \mathcal{CN}\left(0, \sum_{\ell} p_\ell\right) \quad (13a)$$

$$h_{i,n} \sim \mathcal{CN}(0, 1). \quad (13b)$$

This is consistent with the usual assumptions for i.i.d. models with normalized unit power. We also note the existence and effects of two main sources of correlation: intra-hop (spatial) and inter-hop.

### A. Intra-Hop Spatial Power Correlation

Similar to [4], our model predicts correlation between the multiple channel coefficients. One way to describe it is via the spatial covariance matrix

$$R_{n,m}(\mathbf{p}, \boldsymbol{\theta}) = \mathbb{E}[h_{i,n} h_{i,m}^* | \mathbf{p}, \boldsymbol{\theta}], \quad (14)$$

which, since our model is shift-invariant, depends only on the difference  $d$  between RIS elements:

$$R_d(\mathbf{p}, \boldsymbol{\theta}) = \sum_{\ell=1}^L p_\ell e^{-j\pi d \sin\theta_\ell}. \quad (15)$$

The spatial power correlation can thus be written as

$$c_d = \text{Corr}(|h_{i,n}|^2, |h_{i,n+d}|^2) \quad (16a)$$

$$= \mathbb{E}[|R_d(\mathbf{p}, \boldsymbol{\theta})|^2] \quad (16b)$$

$$= \mathbb{E}\left[\sum_{\ell} p_\ell^2\right] + \mathbb{E}\left[\sum_{k \neq \ell} p_k p_\ell\right] |\mathbb{E}[e^{-j\pi d \sin\theta}]|^2 \quad (16c)$$

$$= \beta_L + (1 - \beta_L) J_0(\pi d)^2, \quad (16d)$$

where  $J_0$  is the Bessel function of the first kind and zeroth order. The coefficient  $\beta_L = \mathbb{E}[\sum_{\ell} p_\ell^2]$  measures the concentration of the scatterer power profile. If the power is uniformly distributed,  $\beta_L = 1/L$ ; if one scatterer dominates,  $\beta_L \approx 1$ . Hence,  $1/\beta_L$  can be interpreted as an effective number of active scatterers. As  $L$  increases with fixed lognormal variance, the normalized power profile becomes less concentrated on average, so  $\beta_L$  decreases with  $L$ .

### B. Inter-Hop Power Correlation

Because of the model assumption of correlated small-scale fading, parametrized by  $\rho^2$ , there is also an inter-hop correlation effect between the BS-RIS and the RIS-UE hops. This can be quantified by a similar correlation metric computed between corresponding elements:

$$c_\rho = \text{Corr}(|h_{1,n}|^2, |h_{2,n}|^2) \quad (17a)$$

$$= \mathbb{E}\left[\sum_{k,\ell} p_k p_\ell \mathbb{E}[r_{1,k}^2 r_{2,\ell}^2]\right] - 1 \quad (17b)$$

$$= \rho^2 \beta_L. \quad (17c)$$

We note that, while (13a), (16d) and (17c) completely describe the power-correlation matrix structure for the  $2N$  channel envelopes, it is not sufficient to fully characterize their joint distribution, i.e., it does not define a unique geometry-free abstraction to generate samples of  $h_{i,n}$  that preserves the same probability density for  $h$ .

### C. Effect on Phase-Aligned Cascaded Gain

Because the resulting cascaded channel for the RIS-assisted communications system is a single SISO scalar  $h$ , we can evaluate the theoretical impact of  $c_d$  and  $c_\rho$  as defined above

on the distribution of  $h$ . One of the relevant metrics on which this effect can be quantified is the normalized gain statistic

$$G(\rho) = \frac{\mathbb{E}[h^2]}{N^2} \quad (18a)$$

$$= \frac{1}{N^2} \left( \mathbb{E} \left[ \left( \sum_n |h_{1n}| |h_{2n}| \right)^2 \right] \right) \quad (18b)$$

$$= \frac{1}{N^2} \left( \sum_n \mathbb{E}[X_n^2] + \sum_{n \neq m} \mathbb{E}[X_n X_m] \right), \quad (18c)$$

where  $X_n = |h_{1n}| |h_{2n}|$ .

The diagonal term  $\mathbb{E}[X_n^2]$  is equal to  $1 + c_\rho$  by definition. The off-diagonal terms once again depend only on the differences  $d = m - n$ , by stationarity across the RIS elements. Let  $K_i(d) = \mathbb{E}[|h_{i,n}| |h_{i,n+d}| | \alpha_i, \theta]$ . Then,

$$G(\rho) = \frac{1 + c_\rho}{N} + \frac{2}{N^2} \sum_{d=1}^{N-1} (N - d) \mathbb{E}[K_1(d) K_2(d)]. \quad (19)$$

The off-diagonal terms are simultaneously affected by the spatial correlation  $c_d$ , which increases each  $K_i$  individually, and by the inter-hop correlation  $c_\rho$ , which increases the resulting expected products.

Although (19) is exact, each  $K_i$  is an  $L$ -dimensional phase integral with no simple analytical form outside of numerical approximations. The following special cases allow for simplified expressions.

1) *Single scatterer*: In this case,  $L = 1$  and  $\beta_L = 1$ , all channel magnitudes are the same in each hop. This means  $h = N r_1 r_2$  and

$$G(\rho | L = 1) = 1 + \rho^2. \quad (20)$$

2) *Uncorrelated hops*: When there is no inter-hop correlation ( $\rho = 0$ ), the off-diagonal terms can be computed by observing that, since  $h_{i,n} \sim \mathcal{CN}(0, 1)$  and  $\text{Corr}(|h_{i,n}|^2, |h_{i,n+d}|^2 | \mathbf{p}, \theta) = |R_d(\mathbf{p}, \theta)|^2$ , then

$$\mathbb{E}[|h_{i,n}| |h_{i,n+d}| | \mathbf{p}, \theta] = \frac{\pi}{4} {}_2F_1 \left( -\frac{1}{2}, -\frac{1}{2}; 1; |R_d(\mathbf{p}, \theta)|^2 \right), \quad (21)$$

where  ${}_2F_1$  is the hypergeometric function. Using the shorthand  $q_d(\mathbf{p}, \theta) = {}_2F_1(-1/2, -1/2; 1; |R_d(\mathbf{p}, \theta)|^2)$ , we can write

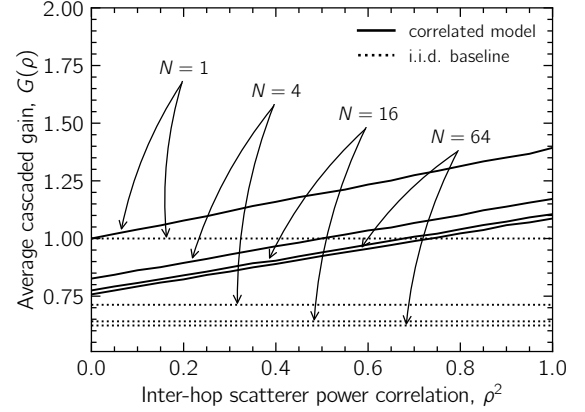
$$G(0) = \frac{1}{N} + \frac{\pi^2}{8N^2} \sum_{d=1}^{N-1} (N - d) \mathbb{E}[q_d(\mathbf{p}, \theta)^2]. \quad (22)$$

3) *i.i.d. baseline*: For the scenario with no inter- and intra-hop correlation,  $h_{i,n} \sim \mathcal{CN}(0, 1)$  i.i.d., so  $\mathbb{E}[X_n^2] = 1$  and  $\mathbb{E}[X_n X_m] = \pi^2/16$ , and (19) simplifies to

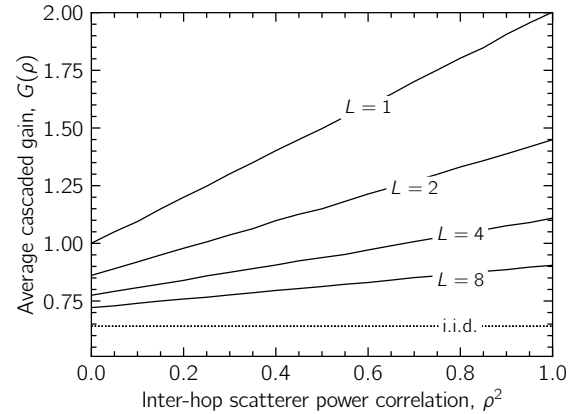
$$G_{i.i.d.} = \frac{1}{N} + \frac{N-1}{N} \frac{\pi^2}{16}. \quad (23)$$

#### IV. SIMULATION STUDIES

We now assess the effect of inter-hop scatterer-power correlation, parametrized by  $\rho^2$ , on two main metrics: the average channel gain and the outage probability. In what follows, the simulation findings are discussed in detail for both metrics.



(a)



(b)

Fig. 3: Behavior of the gain statistic  $G(\rho)$  for different values of (a)  $N$  ( $L = 4$  fixed) and (b)  $L$  ( $N = 16$  fixed).

Each point is estimated using  $10^6$  Monte Carlo realizations. The i.i.d. baseline is obtained by generating independent  $\mathcal{CN}(0, 1)$  coefficients for both hops, without intra-hop or inter-hop correlation.

##### A. Normalized Cascaded Gain

Fig. 3 shows the normalized cascaded gain  $G(\rho) = \mathbb{E}[h^2]/N^2$  for different choices of  $N$  and  $L$ . The fully i.i.d. baseline is shown for reference. This baseline should not be confused with the  $\rho = 0$  case of the proposed model. When  $\rho = 0$ , the small-scale powers of corresponding scatterers in the two hops are uncorrelated, but each hop still exhibits intra-hop spatial correlation due to the finite angular scattering structure. Therefore, the difference between  $G(0)$  and  $G_{i.i.d.}$  quantifies the impact of spatial correlation alone. This separation shows that independent-element RIS models can be inaccurate even before inter-hop correlation is introduced.

Increasing  $\rho^2$  further increases  $G(\rho)$ . Thus, under perfect phase compensation, inter-hop power correlation improves the average phase-aligned cascaded gain. This occurs because strong scatterer realizations in one hop are more likely to coincide with strong realizations in the other hop, increasing the products  $|h_{1,n}| |h_{2,n}|$  that add coherently after RIS phase optimization. This gain increase should not, by itself, be

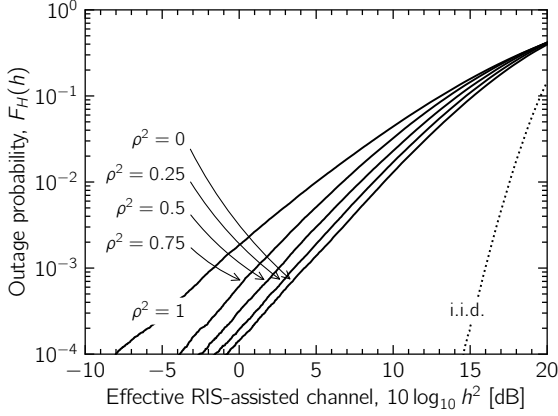


Fig. 4: Outage probability for different values of  $\rho^2$  and for the i.i.d. baseline, with  $N = 16$  elements and  $L = 4$  scatterers.

interpreted as a reliability improvement. As shown in Fig. 4, the same correlation also increases the probability of jointly weak cascaded realizations, degrading the performance metric on the left tail of the CDF.

For a fixed number of scatterers ( $L = 4$ ), Fig. 3a suggests that, as the number of RIS elements  $N$  increases,  $G(0)$  decreases asymptotically towards a positive floor, whereas the gain variations  $G(\rho) - G(0)$  are barely affected. As  $N$  increases, the  $G(\rho)$  becomes increasingly dominated by the off-diagonal terms in (19), while the diagonal contribution scales as  $1/N$ . This explains why the curves approach an asymptotic regime.

Fig. 3b complements this observation by showing, for a fixed value of  $N = 16$ , the effects of changing the total number of scatterers  $L$ . As  $L$  increases, the scatterer power profile becomes less concentrated on average, reducing  $\beta_L$  and consequently reducing the sensitivity to inter-hop correlation.

### B. Outage Probability

Fig. 4 shows the cumulative distribution function of the cascaded channel power for different values of  $\rho^2$ . Although larger  $\rho^2$  increases the average gain, it also worsens the lower tail of the distribution, indicating reduced diversity gain. Therefore, at low outage probabilities, an independent-hop model can be optimistic: it predicts a smaller signal-to-noise ratio margin than is required when the two hops are positively correlated. This illustrates that inter-hop correlation affects not only the mean cascaded gain but also the diversity behavior of the RIS-assisted channel.

## V. CONCLUSIONS

This paper investigated the impact of inter-hop power correlation in a phase-optimized RIS-assisted SISO channel. We proposed a shared-scatterer geometry-based model in which the BS-RIS and RIS-UE hops share RIS-side angular support and scatterer power weights, while the small-scale fading powers of corresponding scatterers are correlated through a tunable parameter. The resulting model captures both intra-hop spatial correlation across RIS elements and inter-hop power correlation between the two cascaded hops.

The analysis and simulations show that inter-hop correlation has a mixed effect. It increases the normalized average cascaded gain because strong fading components tend to occur simultaneously in both hops. However, it also worsens outage performance by increasing the probability of jointly weak cascaded realizations. Consequently, independent-hop models may provide optimistic reliability predictions even when their average-gain predictions appear reasonable.

Future work should extend the model to MIMO and multiuser RIS systems, incorporate direct-link components, and examine robustness under imperfect channel state information, phase quantization, and suboptimal RIS configurations.

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