How Long Can RIS Work Effectively: An Electronic Reliability Perspective

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***Abstract*—In this paper, from an electronic reliability perspective, non-residual stochastic hardware aging (HA) effects are introduced to reconfigurable intelligent surfaces (RISs) aided communication systems, for characterizing the life cycle of the RIS. Different from traditional residual impairment factors such as RIS phase imperfections and transceiver noises, the impact of the stochastic HA effect on the RIS is related to RIS runtimes and lifetimes. Given this background, we first propose a Rician channel model for the RIS-aided system with the stochastic HA effect. Then, the definition for the lifetime of the RIS is mathematically given as the time at which 63.2% of the elements expire. Besides, closed-form achievable rate expression is also derived. Analytical and simulated results unveil an important insight that throughout the life cycle of the RIS, the residual impairment dominates when the runtime is shorter than the lifetime, otherwise the stochastic HA effect should be paid more attention to. This work can be regarded as the first guideline for evaluating and predicting the whole life cycle performance of the RIS-assisted system.**

***Index Terms*—Reconfigurable intelligent surface, impairment factor, stochastic hardware aging effect, electronic reliability, achievable rate**

I. INTRODUCTION

Reconfigurable intelligent surfaces (RISs), also known as intelligent reflecting surfaces [1] and large intelligent surfaces [2], are becoming an innovative and promising solution that creates a smart radio environment [3]. In particular, the RIS is a planar surface that is comprised of massive sub-wavelength passive reflectors, each causing amplitude and/or phase shifts on the incident electromagnetic wave independently and instantaneously [1]. Thus, by utilizing the RIS, it is possible to reorient the reflected signal for improving transmission performance in the next-generation communication system [4].

Although recent RIS literature mainly focuses on the theoretical side, some hardware prototypes have already been developed to validate the practicality and effectiveness of the RIS. Dai, *et al* [5] first developed an RIS prototype with 256 two-bit elements, which not only leads to a 21.7 dBi antenna gain when the carrier frequency is 2.3 GHz but also reduces the power consumption significantly. Tang, *et al* [6] proposed an analytical free-space path loss model for RIS-aided systems and validated its correctness by measuring a well-designed RIS hardware. Besides, Pei, *et al* [7] established an RIS prototype consisting of 1100 elements working at 5.8 GHz band, and measured that it can provide a 26 dB power gain compared to a same-size copper plate. Liu, *et al* [8] confirmed the feasibility and effectiveness of the RIS to improve received signal qualities across different frequency ranges through field trial results.

It should be emphasized that there is always a mismatch between theoretical and practical results [5]–[8], due to practical impairment factors (IFs) [3]. Specifically, for the RIS-aided system, there are three major categories of IFs [9]–[11], i.e., RIS IF (RIF), transceiver IF (TIF), and phase-dependent amplitude variations (PAV). The RIF can be considered as random phase errors following a uniform distribution [9]. The TIF includes the combined impact of all the imperfect transceivers and can be modeled as additive Gaussian noise [10]. Moreover, the PAV denotes the non-linear relationship between the phase and amplitude of the RIS [11].

The IFs above are all residual; that is to say, they always exist in the RIS-aided system and are not related to the runtime [3]. In practical environments, however, non-residual IFs [12], [13] also exist in electronic devices, say, the RIS-aided system [14]. In particular, non-residual IFs are mainly runtime-related random failures. Since the RIS is an electronic component, its lifespan is limited. Therefore, it is necessary to consider both its runtime and lifetime [12]. To the best of our knowledge, there are few studies on non-residual IFs of the RIS-aided system. Wang, *et al* [14] first introduced the runtime-related HA effect to the RIS-aided system, but the proposed model is deterministic, which is not that realistic. Besides, the lifetime of the RIS, which is crucial to the RIS hardware, should be defined clearly.

Motivated by the above reasons, in this paper, we propose a framework of the RIS-aided system with residual and non-residual IFs, to mimic practical RIS behaviors throughout its whole life cycle. Our contributions are as follows:

- First, from an electronic reliability perspective, we introduce a new non-residual IF for the RIS, i.e., the stochastic HA effect, to describe runtime-related hardware degradations and failures. Different from other conventional residual IFs, the stochastic HA effect mainly reflects the RIS element failure that along with the runtime goes on. Besides, we mathematically show that the lifetime of the RIS is the runtime that 63.2% of elements fail.
- Secondly, we propose a Rician channel model for RIS-aided communications with the residual IFs, i.e., the RIF, the TIF, and the PAV, and the non-residual IF, i.e., the stochastic HA effect. Compared with previous works,

the proposed model can effectively reflect the impact of runtime and lifetime on the RIS-aided system.

- Lastly, we show that the stochastic HA effect, rather than the other residual IFs, is the main IF when the runtime is far beyond the lifetime. We also obtain the closed-form achievable rate (ACR) of the proposed model.

The main insights of this paper are as follows. First, the RIS can work effectively longer than its designed lifetime. Second, when the runtime is smaller than the lifetime, the residual IFs dominate, otherwise the non-residual IF, i.e., the stochastic HA effect, is more disruptive.

Notation: $\lfloor\cdot\rfloor$ and $\lceil\cdot\rceil$ are floor and ceil functions, respectively. Besides, $|\cdot|$ denotes absolute value, $\|\cdot\|$ is l_2 norm, $[\cdot]^{\mathsf{T}}$ is transpose operation, $\jmath \triangleq \sqrt{-1}$, $\sin(\cdot)$ and $\cos(\cdot)$ are respectively sine and cosine functions, and $\exp(\cdot)$ is exponential function. Moreover, $\mathcal{U}$, $\mathcal{CN}$, and $\mathbb{E}\{\cdot\}$ represent uniform distribution, complex Gaussian distribution, and expectation function, respectively.

II. CONVENTIONAL RESIDUAL IMPAIRMENT FACTORS

In this section, we first introduce three conventional residual IFs of the RIS-aided communication system. Then, a typical RIS-aided system model containing these traditional hardware impairments is introduced.

A. RIS Impairment Factor

Consider an RIS with M identical elements. The residual IF of the RIS (RIF), which is caused by intrinsic hardware imperfections and channel estimation errors, can be modeled as random phase error $\gamma_m \sim \mathcal{U}[-\alpha, \alpha]$ [9], [10], where $\alpha \triangleq 2^{-q}\pi$ with $q \geq 1$ and $m = 1, 2, \ldots, M$. Therefore, the phase shift of the m-th element with RIF is $(\phi_m + \gamma_m)$, where ϕ_m is the designed phase shift [9], [10].

B. Transceiver Impairment Factor

The residual transceiver IF (TIF) includes the IFs in transceivers [9], [10]. In more specific terms, the TIF denotes distortion noises generated by the transceiver resulting from imperfect modeling, which can be modeled as $\eta_t \sim \mathcal{CN}(0, \Upsilon)$ and $\eta_r \sim \mathcal{CN}(0, V)$, where Υ and V are respectively a factor of proportionality ι_t times transmit power and a factor of proportionality ι_r times received power [9], [10].

C. Phase-Dependent Amplitude Variations

For the m-th element of the RIS where $m = 1, 2, \ldots, M$, the reflection coefficient ς_n can be obtained as [11]

$$\varsigma_m = \frac{X_m - X_0}{X_m + X_0}, \tag{1}$$

where X_0 and X_m are the free space and the m-th element impedance, respectively. In recent studies, the popular reflecting model of the RIS can be denoted as $\beta(\phi_m)\exp(-\jmath\phi_m)$ [3] where $\phi_m \in [0, 2\pi)$ and $\beta_m(\phi_m) \in [0, 1]$ are respectively the phase shift and the amplitude of the m-th element. This model, however, cannot mathematically reflect the relationship between the phase and the amplitude. Fortunately, $\beta_m(\phi_m)$ can be further approximated as [11], [15]

$$\beta(\phi_m) = (1 - b)\left(\frac{\sin(\phi_m - c) + 1}{2}\right)^a + b, \tag{2}$$

where $a \geq 0$ is the steepness factor, $b \in [0, 1]$ is the minimum amplitude, and $c \geq 0$ is the horizontal distance between $\pi/2$ to π. Since b is more sensitive in (2) compared to a[1], we assume $a = 1$ in the rest of this paper for ease of calculation.

D. System Model with Residual Impairment Factors

Suppose a downlink single-input single-output (SISO) communication system with an RIS with M identical reflectors. The antenna of the transceiver and the RIS are all isotropic. The BS, the user, and the m-th RIS element locate respectively in D_{BS}, D_{user}, and D_m, where $m = 1, 2, \ldots, M$. Certain barriers, like buildings, trees, and vehicles, surround the transceiver and the RIS [2], hence the Rician channel model in this paper contains two parts. The first part is the direct link h_d, which refers to the link between the BS and the user. Another one is the cascaded RIS link, which includes the paths from the BS and the RIS, i.e., g_m, and from the RIS to the user, i.e., h_m. Note that h_d, g_m, and h_m all include light-of-sight (LoS) and non-light-of-sight (NLoS) components. Besides, statistical channel state information is fully utilized in both the transceiver and the RIS [2].

We focus on the LoS part of h_d at first. The path loss of h_d can be computed as [9] $A_0 = \lambda/(4\pi d_0)$, where $d_0 = \|D_{\text{user}} - D_{\text{BS}}\|$ and λ is carrier wavelength. The time delay of the direct link is $\tau_0 = d_0/\varrho$, where ϱ is the speed of light. Thus, the phase of the LoS part of the direct link can be obtained as $h_d^{\text{LoS}} = \exp\big(-\jmath 2\pi f_c \tau_0\big)$. Besides, the NLoS part of h_d, i.e., h_d^{NLoS}, follows complex Gaussian distribution $\mathcal{CN}(0, 1)$. Let κ_d be the Rician factor for the direct link, then the h_d can be achieved as

$$h_d = A_0\left(\sqrt{\frac{\kappa_d}{\kappa_d + 1}}h_d^{\text{LoS}} + \sqrt{\frac{1}{\kappa_d + 1}}h_d^{\text{NLoS}}\right). \tag{3}$$

Secondly, with the same structure with h_d, the m-th BS-RIS link, g_m, and the m-th RIS-user link, h_m, can be obtained as

$$g_m = A_{\text{BS}}^m\left(\sqrt{\frac{\rho_m}{\rho_m + 1}}g_m^{\text{LoS}} + \sqrt{\frac{1}{\rho_m + 1}}g_m^{\text{NLoS}}\right), \tag{4}$$

and

$$h_m = A_m^{\text{user}}\left(\sqrt{\frac{\kappa_m}{\kappa_m + 1}}h_m^{\text{LoS}} + \sqrt{\frac{1}{\kappa_m + 1}}h_m^{\text{NLoS}}\right), \tag{5}$$

respectively. Note that A_{BS}^m and A_m^{user} are path losses of g_m and h_m, respectively, and $g_m^{\text{NLoS}}, h_m^{\text{NLoS}} \sim \mathcal{CN}(0, 1)$. Therefore, the total channel h can be written as

$$h = h_d + \sum_{m=1}^{M} h_m \psi_m g_m, \tag{6}$$

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[1] For example, when b is fixed to 0.5, the power loss between $a = 1.6$ and 2 is just 0.2 dB. But when a equals 2, the power loss between $b = 1$ and 0.5 is 3.2 dB. See Table I in [11] for more details.

where $\psi_m = \beta(\phi_m + \gamma_m)\mathsf{exp}(-\jmath(\phi_m + \gamma_m))$ is the practical RIS phase shift with the RIF γ_m.

Finally, the received signal y with the residual IFs can be obtained as

$$y = h\left(\sqrt{P}x + \eta_t\right) + \eta_r + \omega, \tag{7}$$

where P is the transmit power, x stands for the unit-power signal symbol with $\mathbb{E}\{|x|^2\} = 1$, $\eta_t \sim \mathcal{CN}(0, \Upsilon)$, where $\Upsilon = \iota_t P$, $\eta_r \sim \mathcal{CN}(0, V)$, where $V = \iota_r P|h|^2$, and ω is additive white Gaussian noise (AWGN) with the variance σ^2.

III. STOCHASTIC HARDWARE AGING ON RIS

In Section II, we discuss the conventional residual impairments and introduce a downlink SISO RIS-aided system. In practice, however, non-residual runtime-related hardware degradations also exist in electronic devices [12]–[14]. In this section, we first describe the stochastic HA effect, then we introduce this effect into the RIS-aided system in (7).

A. *Stochastic Hardware Aging Effects*

The stochastic HA effect mainly denotes the growth of runtime-related random failures (damages) for RIS reflectors [12], [13]. In terms of the total runtime t, the probability density function (PDF) of the failure rate for one single RIS reflector is often characterized by *Weibull distribution*. This is because it is one of the most popular statistical distributions in reliability theory, and can fit different life cycle characteristics by adjusting the parameters [13]. Thus, the PDF can be expressed as [12]

$$f(t) = \begin{cases} \rho L^{-\rho} t^{\rho-1} \mathsf{exp}(-(\frac{t}{L})^{\rho}) & \text{for } t \geq 0 \\ 0 & \text{for } t < 0, \end{cases} \tag{8}$$

where $L \geq 0$ is the expected lifetime of the RIS element, $\rho \in [1, 3.5]$ is the shape parameter [12]. It is noteworthy that the element failure in this paper can be treated as $\phi \sim \mathcal{U}[0, 2\pi)$ and $\beta \sim \mathcal{U}[0, 1]$ [9]. Based on $f(t)$, the damaged element number can be obtained as Proposition 1 as follow.

Proposition 1: Consider an RIS with M elements, and after runtime t, the expected number of undamaged elements is

$$N(t) = \left\lfloor (1 - \mu) \cdot M \cdot \mathsf{exp}((-\frac{t}{L})^{\rho}) \right\rfloor \tag{9}$$

Proof: Considering the RIS has been operated t hours, the corresponding reliability function can be obtained as $C(t) = 1 - \int_0^t f(t)dt$. Consequently, according to (8), $\int_0^t f(t)dt = 1 - \mathsf{exp}(-(\frac{t}{L})^{\rho})$, thus $C(t) = \mathsf{exp}((-\frac{t}{L})^{\rho})$. Then, the instantaneous failure (hazard) rate can be obtained as $f(t)/C(t) = \rho L^{-\rho} t^{\rho-1}$. Recall the RIS contains M identical elements and the early external failure rate is μ, then the expected number of undamaged elements $N(t)$ after the runtime t can be obtained as (9). ■

Based on Proposition 1, we then define the RIS lifetime as Proposition 2.

Proposition 2: The lifetime L of the RIS can be defined as the time at which 63.2% of the elements expire.

Proof: Let $\mu = 0$ and substitute $t = L$, then the corresponding reliability function $C(t) = \mathsf{exp}(-1) = 0.368$. Hence the number of expired elements is about 63.2%. ■

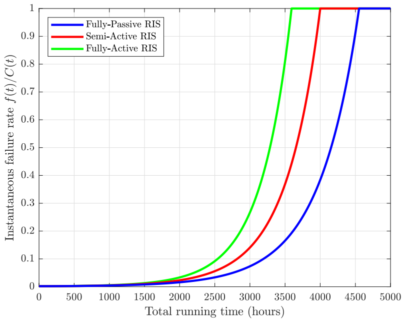

Fig. 1. Instantaneous failure rates for different types of RIS. $L = 500$ hours.

Remark: Different types of RIS may have different reliability parameters. Table I shows ρ and μ for fully passive, semi-active, and fully active RISs[2]. Fig. 1. illustrates the instantaneous failure rates for the three types of RISs in terms of different ρ. For a fair comparison, the lifetimes of the three categories are set the same, i.e., $L = 500$ hours. It can be seen that when $t \leq L$, the instantaneous failure rate is constant, which implies all RISs work along with a smooth failure rate. However, when t gradually increases, the instantaneous failure rate increases rapidly, which leads to a serious performance decrease. Besides, the fully active RIS has the highest ρ and μ since active electronic components are easier to fail during their whole life cycle [12]. It should be emphasized that μ and ρ are independent of one another [13].

TABLE I
RELIABILITY PARAMETERS IN (9) FOR DIFFERENT TYPES OF RIS

Types of RIS	ρ	μ
Fully passive RIS	3.5	0.01
Semi-active RIS	4	0.05
Fully active RIS	4.5	0.07

B. *RIS-aided System with Stochastic Hardware Aging*

Suppose the runtime of the RIS with M elements is t hours. According to Proposition 1, the survived element number is $N(t)$. Then, let $S(t) = M - N(t)$, the total channel expression h in (6) can be rewritten as

$$\bar{h}(t) = h_d + \underbrace{\sum_{n=1}^{N(t)} h_n \psi_n g_n}_{\text{Undamaged part}} + \underbrace{\sum_{s=1}^{S(t)} h_s \bar{\psi}_s g_s}_{\text{Damaged part}}, \tag{10}$$

where for the damaged part, $s = 1, 2, \ldots, S(t)$, $\bar{\psi}_s = \bar{\beta}_s \mathsf{exp}(-\jmath \bar{\phi}_s)$, $\bar{\beta}_s \sim \mathcal{U}[0, 1]$, and $\bar{\phi}_s \sim \mathcal{U}[0, 2\pi]$. It can be seen

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[2] It should be noted that they are theoretical parameters based on their physical structures. Measuring practical parameters (e.g., μ and ρ) using hardware validations for different types of RIS is left open to future works. However, fully (semi-) active RIS operates in stronger electric currents, so there should be a greater probability of element failure [12], [13].

that the damaged part of the RIS loses its ability to beamform. As the runtime t increases, $N(t)$ diminishes. When the t is long enough, $N(t) = 0$, $S(t) = M$, the RIS becomes a random scatterer. Accordingly, the received signal at this time can be obtained as $\bar{y}(t) = h_d + \sum_{s=1}^{S(t)} h_s \bar{\psi}_s g_s(\sqrt{P}x + \eta_t) + \eta_r + \omega$.

IV. ACHIEVABLE RATE ANALYSIS

In this section, we give the analytical expression of the achievable rate of the RIS-aided system with stochastic HA effect in Section III. Considering the channel $\bar{h}(t)$ in (10), then the ACR can be obtained as

$$R(t) = \mathbb{E}\left\{ \log_2 \left(1 + \frac{P|\bar{h}(t)|^2}{P(\iota_t + \iota_r)|\bar{h}(t)|^2 + \sigma^2} \right) \right\}. \tag{11}$$

Therefore, we can have Theorem 1 as follow.

Theorem 1: Consider a practical channel for the RIS-aided system with RIF, TIF, PAV, and stochastic HA effects, as $\bar{h}(t)$. For the healthy elements $N(t)$, the optimal ϕ_n is design as $2\pi(f_c(\tau_0 - \tau_n) + \lceil f_c(\tau_n - \tau_0) \rceil)$ [9], where τ_n is the delay of the n-th cascaded link and $n = 1, 2, \ldots, N(t)$. Then, the ACR in (11) can be approximated as

$$\bar{R}(t) \approx \log_2 \left(1 + \frac{PQ(t)}{P(\iota_t + \iota_r)Q(t) + \sigma^2} \right), \tag{12}$$

where Q is expressed as (13), shown at the top of the next page. Note that in (13), we define $A_{m(n)} = A_{\mathrm{BS}}^{m(n)} A_{m(n)}^{\mathrm{user}}$. Besides, K_1 to K_4 denote $\sqrt{\frac{\kappa_d}{\kappa_d+1}}$, $\sqrt{\frac{1}{\kappa_d+1}}$, $\sqrt{\frac{\kappa_m}{\kappa_m+1}}$, $\sqrt{\frac{1}{\kappa_m+1}}$, respectively. G_1 and G_2 are $\sqrt{\frac{\rho_m}{\rho_m+1}}$, $\sqrt{\frac{1}{\rho_m+1}}$, respectively. We omit (t) for simplicity.

Proof: Recall $\gamma_{n(s)} \sim \mathcal{U}[-\alpha, \alpha]$, then $\mathbb{E}\{\exp(-\jmath\gamma_{n(s)})\} = \mathbb{E}\{\cos(\gamma_{n(s)})\} - \jmath\mathbb{E}\{\sin(\gamma_{n(s)})\}$. Using the Taylor series expansion $\cos(z) \approx 1 - z^2/2 + z^4/24$, we have $\mathbb{E}\{\exp(-\jmath\gamma_{n(s)})\} = (1/2\alpha)\int_{-\alpha}^{\alpha} \cos(\gamma_{n(s)}) d\gamma_{n(s)} = 1 - \alpha^2/6 + \alpha^4/120$. For the healthy elements $N(t)$, we assume $(\phi_n - c) \sim \mathcal{U}[-c, 2\pi - c]$, and $\gamma_{n(s)}$ in the amplitude and the phase are independent. For the failed elements $S(t)$, the amplitude and the phase all follow uniform distributions. Besides, the random scattering gain from the failed elements $S(t)$ is ignored since it is relatively small. Consider the channel $\bar{h}(t)$ in (10) and after some simplifications, (13) is obtained. ■

V. NUMERICAL EVALUATIONS AND DISCUSSIONS

In this section, numerical simulation results are offered to validate the analytical results in Sections II, III, and IV.

Suppose the BS, the RIS, and the user are all located in the three-dimensional Cartesian coordinate system. Default setup parameters in this section can be found in Table II unless otherwise specified. Besides, the positions of the BS and the RIS are fixed but for the location of the user, two different setups are assumed to ensure the analytical results are more convincing. The first case is the user moves slowly along the x-axis from [-250 m, 2 m, 20 m]$^{\mathsf{T}}$ to [250 m, 2 m, 20 m]$^{\mathsf{T}}$, the total moving time can be omitted compares to the usage time t, and Doppler effect is not considered. Another scenario is the static user with the position [0 m, 2 m, 20 m]$^{\mathsf{T}}$.

TABLE II
SIMULATION PARAMETERS

Parameters	**Values**
Position of the BS (D_{BS})	[0 m, 20 m, 50 m]$^{\mathsf{T}}$
Position of the user (D_{user})	[0 m, 2 m, 20 m]$^{\mathsf{T}}$ / moving
Position of the $n(s)$-th element ($D_{\mathrm{n(s)}}$)	See Eq. (1) in [9]
The center of RIS	[0 m, 15 m, 0 m]$^{\mathsf{T}}$
PAV parameters (a, b, and c)	1, 0.8, 0.43π [11]
Transmit power (P)	20 dBm
AWGN noise power (σ^2)	-80 dBm
Carrier frequency (f_c)	2.4 GHz
Undamaged number of elements when $t = 0$	64^2
Rician factors (κ_d, $\kappa_{n(s)}$, and $\rho_{n(s)}$)	10 dB, 10 dB, 10 dB
RIF (q)	2
TIF (ι_t, ι_r)	0.01^2, 0.01^2
Typical shape parameter (ρ)	3.5
Early external failure rate (μ)	0.01
RIS lifetime (L)	500 hours
RIS runtime (t)	2000 hours
Realization number	5000

A. The First Case

Fig. 2. demonstrates the ACR for the moving user (i.e., the first case). Several observations can be found. First, all ACRs first increase and then decrease, due to the distance-dependent channel gains A_0 and A_n in (13). Second, when the user approaches the BS and the RIS, i.e., the system in a high signal-to-noise-ratio (SNR) region, the TIF is the main degradation factor, compared with other residual IFs. However, when the system is with a low SNR, the RIF dominates. Besides, it can be seen that the stochastic HA also diminishes system performance. We emphasize that this aging effect is related to operation times, hardware designs, and usage environments, rather than the transmit power P or SNR. Besides, the Monte Carlo (11) and the analytical (12) ACRs (i.e., $R(t)$ and $\bar{R}(t)$) match well, which validates the correctness of Theorem 1.

B. The Second Case

Fig. 3. shows the ACR performance with different RIFs q, as runtime t goes on. It is shown that, first, the RIF decreases the ACR, and $q = 1$ (i.e., $\alpha \sim \mathcal{U}[-\pi/2, \pi/2]$) performs the worst, as expected. Second, it is important to point out that the RIF is not related to the runtime. In other words, it exists even if t is almost 0. The reason is the RIF is residual noise. However, when the RIS runs enough time, all cases lose their beamforming ability and become diffuse reflectors. It implies that when $t \gg L$, the stochastic HA effect dominates IFs.

Fig. 4. illustrates the ACR performance along with runtime t increases, with different PAV factors b. Similar to the RIF, b can also be regarded as one of the residual noises. Therefore, it exists all the life cycle of the RIS. $b = 0.2$ and $b = 1$ perform the worst and the best, as expected. Besides, when $t > 500$, all cases start to be identical gradually and lose their abilities for smart reflecting. This observation confirms that the stochastic HA effect is more important when the RIS is wearing out.

Fig. 5. demonstrates the ACR performance with different lifetimes L, as runtime t goes on. Clearly, the decrease pattern

$$Q(t) \approx A_0^2 + (\frac{1+b}{2})^2(1-\alpha^2/6+\alpha^4/120)^2 K_3^2 G_1^2 \Big(\sum_{n=1}^{N(t)} A_n\Big)^2 + \tag{13}$$
$$(\frac{1+b}{2})^2(1-\alpha^2/6+\alpha^4/120)^2\big(K_3^2K_4^2+K_4^2G_1^2+K_4^2G_2^2\big)\sum_{n=1}^{N(t)} A_n^2 + (1+b)(1-\alpha^2/6+\alpha^4/120)K_1K_3G_1A_0\sum_{n=1}^{N(t)} A_n.$$

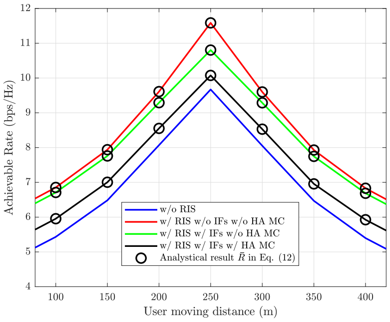

Fig. 2. ACR for moving user. $t = 500$ hours.

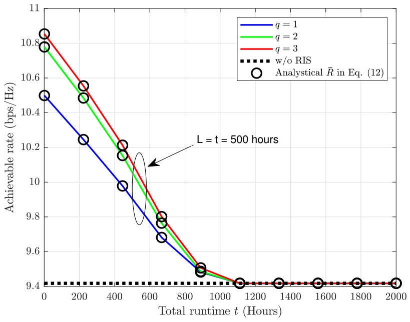

Fig. 3. Fixed user. ACR for different q.

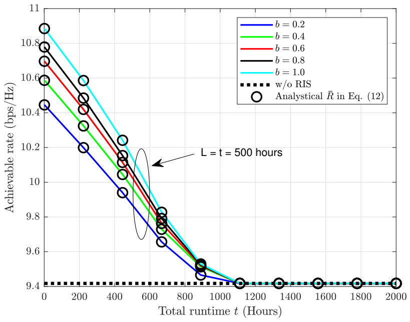

Fig. 4. Fixed user. ACR for different b.

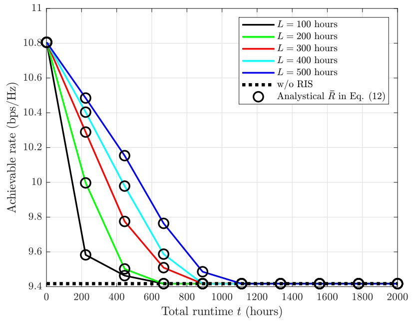

Fig. 5. Fixed user. ACR for different L.

is different from Fig. 3. and Fig. 4., due to the fact that the stochastic HA effect is runtime-related. In particular, when $t = 0$, all cases with different L are with the same achievable rate. In other words, at this stage, the RIS-aided system only contains traditional residual IFs. However, when $t > 0$, the non-residual IF appears and becomes more important when $t \gg L$.

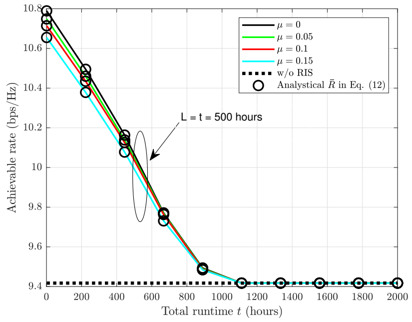

Fig. 6. Fixed user. ACR for different μ.

Fig. 6. illustrates the ACR performance with different early external failure rates μ, as runtime t goes on. Manufacturing defects are usually responsible for this type of failure [12], [13]. However, it should be emphasized that it is an important part of the non-residual noise, although its behavior is similar to the residual ones.

Fig. 7. shows the ACR performance with different typical shape parameters ρ along with runtime t increases. We can see that ρ is more sensitive to the system performance when $t > 500$, i.e., the total runtime beyond the lifetime of the RIS. Hence, measuring suitable ρ for different types of RIS via hardware testing is of great importance in practice.

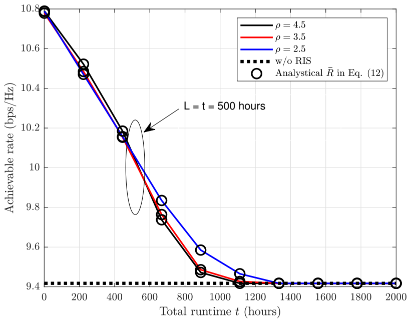

Fig. 7. Fixed user. ACR for different ρ.

C. *Fully Passive, Semi-Active, and Fully Active RISs*

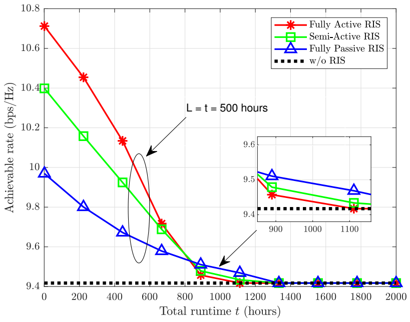

Fig. 8. Fixed user. ACRs for the three types of RIS. $M = 48^2$, and other parameters can be found in Tables I and II.

Fig. 8. compares the ACRs of fully passive, semi-active, and fully active RISs. As expected, when $t < 500$, all ACRs decrease peacefully and the fully active RIS has the highest ACR because of its active elements. Besides, the fully passive RIS performs worst since it can only reflect, rather than amplify the incident wave. However, when t increases long enough, things become totally different. In particular, when $t > 900$, the semi-active RIS performs better than the fully-active RIS. This is because the fully active element has a higher failure rate when the RIS works for a long time and is wearing out seriously. This result reveals an important insight that, a more promising performance enhancement by the fully (semi-) active RIS only happens when the runtime t is not too large. Thus, the life cycle should be carefully considered when designing an RIS. In other words, when we want to deploy an RIS and it will lack maintenance (e.g., autonomous RIS), the fully passive and semi-active RISs are more suitable than the fully active RIS. Similarly, when $1100 < t < 1200$, the fully passive RIS still can bring several ACR improvements, but the fully active RIS loses all of its beamforming abilities.

VI. CONCLUSION

In this paper, we have introduced the non-residual stochastic HA effect to the RIS-aided system, to describe the RIS life cycle performance. Different from the traditional residual IFs, the stochastic HA effect on the RIS is related to the runtime and the lifetime of the system. Besides, we have defined the lifetime of the RIS as the time at which 63.2% of the elements expire. The analytical and simulated results have unveiled that when the RIS operates during its lifetime region, the residual noise dominates, otherwise the stochastic HA effect is more important. By examining the life cycle of the RIS-aided system, this paper can be regarded as a guideline for predicting and evaluating its performance. Potential further research directions include measuring practical reliability parameters via RIS hardware and how to compensate for the non-residual IFs. Besides, it is worth investigating the impairment behavior of the active RIS-assisted system with the HA effect.

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