On hardware aging for practical RIS-assisted communication systems

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In this letter, reconfigurable intelligent surface (RIS) is studied from an electronic device reliability perspective. Runtimes and lifetimes of the RIS are introduced for the first time as impairment factors that degrade the system performance. In particular, Weibull distributions are used to model the runtime-related hardware aging (HA) effect on the RIS at first. Then, a practical RIS-assisted system model with phase-dependent amplitude variations, residual hardware impairments, and HA effects, is obtained. Besides, closed-form expressions of the received signal power and spectral efficiency for the proposed system are also derived. Analytical and numerical evaluations reveal that the HA effect on the RIS is the major impairment factor when the runtime is beyond the lifetime of the RIS.

Introduction: Reconfigurable intelligent surface (RIS) is a planar array that is made up of many sub-wavelength passive reflecting elements, each of which can cause amplitude and/or phase shift on the incident signal, in real-time, independently [1]. Hence, reflected electromagnetic waves can be reoriented toward the desired direction to enhance transmission performances. As a result of its passive nature and low hardware costs, RIS is shown to be more energy-efficient than other existing technologies [2]. In practical scenarios, residual hardware impairments (HWI) such as phase noise and quantization error limit the system performance [3, 4]. Xing *et al.* [3] considered the HWI that appears at both RIS and transceivers and derived closed-form expressions of the average achievable rate and the RIS utility. Zhou *et al.* [4] analyzed the spectral and energy efficiency of an RIS-assisted downlink system with HWI and showed that the spectral efficiency (SE) is limited due to the HWI even when the number of transceiver antennas and RIS elements grows infinitely large.

The works in [1–4] all assumed the same reflection amplitude regardless of the phase shift for each reflecting element. This is, nevertheless, particularly difficult to achieve because of hardware limitations [5, 6]. In [5], the authors first proposed a practical RIS model in order to capture phase-dependent amplitude variations (PAV), then an optimization problem is formulated and solved in order to minimize the transmit power at the BS. It is noteworthy that the amplitude of the RIS response is sensitive to the phase shift [5]; thus, the influence of the phase HWI would be more serious when considering PAV. A more accurate analytical RIS model for the PAV is presented in [6], which showed that the relationship between the phase and the amplitude of the RIS depends on the geometrical and electrical properties of the designed surface. Note that the impairment factors considered in [3–6] are all regardless of the hardware aging (HA) effect caused by long-term operations. However, based on the reliability theory [7], electrical devices fail more frequently as a result of enough runtimes. Wang *et al.* [8] proposed an RIS-aided model with random failures, but without the connection with the runtime. Sun *et al.* [9] developed diagnostic techniques for RIS systems to locate faulty reflecting elements and retrieve failure parameters. However, [8, 9] did not consider the PAV. In addition, Taghvaee *et al.* [10] examined the RIS reliability problem from an electromagnetic simulation perspective by introducing an error model of the RIS and a general methodology for error analysis. Besides, the authors of [11] showed that when one-third of the elements of the RIS fail, which can be caused by practical imperfections such as the HA after a long-period operation, the system performance is reduced by half.

It is important to consider the runtime and the lifetime of the RIS since as an electronic component, its lifespan is limited [7, 10]. In this letter, we use Weibull distributions to model the runtime-related HA effect of the RIS. Analytical and simulation results show that as the runtime grows, the HA effect becomes more severe, compared with the residual HWI and the PAV. To the best of our knowledge, this work is the first attempt to study the RIS considering the HA effect.

Notations: Superscript $[\cdot]^{\mathrm{T}}$ stands for transpose operation. $\lceil\cdot\rceil$ and $\lfloor\cdot\rfloor$ are the ceil and floor functions, respectively. $|\cdot|$ is the absolute value. Besides, $\jmath \triangleq \sqrt{-1}$, $\mathcal{U}$ is the uniform distribution, $\exp(\cdot)$ is exponential function, and ν is the speed of light. It is noteworthy that in this letter, t refers to the total runtime period instead of an instantaneous time.

System formulation: Consider a RIS with K identical elements. For the n-th element of the RIS where $n = 1, \dots, K$, the reflection coefficient κ_n is given as [5, 6]

$$\kappa_n = \frac{Z_n - Z_0}{Z_n + Z_0}, \tag{1}$$

where Z_0 and Z_n are the free space and the n-th element impedance, respectively. In order to characterize the relationship between the reflection amplitude and phase shift of the n-th element, let the baseband element model of the RIS be $\Phi_n = \beta(\phi_n)\exp(-\jmath\phi_n)$ with the phase shift of the n-th element $\phi_n \in [0, 2\pi)$ and the amplitude $\beta_n(\phi_n) \in [0, 1]$. Therefore, $\beta_n(\phi_n)$ can be expressed as [5]

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

where $a \geq 0$, $b \geq 0$, and $c \geq 0$ are the constants depending on the specific circuit implementation [6]. In particular, a is the steepness factor, b is the minimum amplitude, and c is the horizontal distance between $\pi/2$ to π. Since b is more sensitive in (2) compared to a [5], we assume $a = 1$ in this letter. It can be observed that $\beta(\phi_n) \in [b, 1]$, which is different from the references [1–4, 8, 9] where $\beta(\phi_n) = 1$ was assumed.

The residual HWI of the RIS can be modelled as the random phase error $\gamma_n \sim \mathcal{U}[-\alpha, \alpha]$ [3, 4], where $\alpha \triangleq 2^{-q}\pi$ with $q \geq 1$. Therefore, the phase shift of the n-th element with HWI is $(\phi_n + \gamma_n)$. Note that we ignore the transceiver HWI since it has no impact on Φ_n [3].

The HA effect refers to the increment of the runtime-related random failures for the elements of the RIS. For the total runtime t, the probability density function (PDF) of the failure rate for an element of the RIS can be described by *Weibull distribution*. This is due to the fact that it is arguably the most commonly used statistical distribution in reliability theory, and also has the advantage of being able to fit many different life distributions by modifying the parameters [7]. Thus, the PDF can be expressed as

$$f(t) = \begin{cases} \rho L^{-\rho} t^{\rho-1} \exp\left(-\left(\dfrac{t}{L}\right)^{\rho}\right) & \text{for } t \geq 0 \\ 0 & \text{for } t < 0, \end{cases} \tag{3}$$

where $L \geq 0$ is the expected lifetime of the element, $\rho \in [1, 3.5]$ is the typical shape parameter [7], and t is the total runtime. Therefore, the failure rate can be obtained as $\int_0^t f(t)dt$. Consequently, according to (3), after the runtime t, the failure rate, that is, the probability of failure, is $\int_0^t f(t)dt = 1 - \exp(-(\frac{t}{L})^{\rho})$. Therefore, the undamaged rate is $\exp((-\frac{t}{L})^{\rho})$. Recall the RIS contains K identical elements, then the expected number of undamaged elements $\Gamma(t)$ after the runtime t can be obtained as

$$\Gamma(t) = \left\lfloor K \exp\left(\left(-\frac{t}{L}\right)^{\rho}\right)\right\rfloor, \tag{4}$$

In this letter, we consider a single-input single-output communication system with a single RIS that contains K identical isotropic elements. The direct and the cascaded light-of-sight channels are all deterministic for simplicity. Besides, the PAV of the RIS is modelled as $\beta(\phi_n)$ in (2) and the residual RIS HWI is modelled as γ_n, where $n = 1, \dots, K$. Let's consider first the received baseband signal without HA, which can be expressed as

$$y = S_0\Theta_0 + \sum_{n=1}^{K} S_n\Theta_n\Phi_n + w, \tag{5}$$

where $S_0 = A_0\sqrt{P_t}x$, $\Theta_0 = \exp(-\jmath 2\pi f_c\tau_0)$, $S_n = A_n\sqrt{P_t}x$, $\Theta_n = \exp(-\jmath 2\pi f_c\tau_n)$, and $\Phi_n = \beta(\phi_n+\gamma_n)\exp(-\jmath(\phi_n+\gamma_n))$. P_t is the transmit power, x is the transmit signal with $\mathbb{E}\{|x|^2\}=1$, $\gamma_n \sim \mathcal{U}[-\alpha,\alpha]$, w is additive white Gaussian noise (AWGN) with the power σ^2. Besides, A_0, A_n, τ_0, and τ_n are the channel gain for direct and cascaded links, the time delay for direct and cascaded links, respectively. Specifically,

$$A_0 = \frac{\lambda_c}{4\pi d_0}, \tag{6}$$

where d_0 is the distance between the BS and the user, and λ_c is the wavelength of the carrier signal. Note that we assume the transmitter and the receiver are both equipped with single isotropic antennas. Therefore, we also have

$$A_n = \frac{\lambda_c^2}{16\pi^2 d_{1n}d_{2n}}, \tag{7}$$

where d_{1n} and d_{2n} are the distance from the BS and the n-th element of the RIS, and the one from the n-th element of the RIS to the user, respectively. Besides, $\tau_0 = d_0/\nu$ and $\tau_n = (d_{1n}+d_{2n})/\nu$.

Using (4) and (5), we then obtain the expression of the received signal with the HA effect as

$$y(t) = S_0\Theta_0 + \underbrace{\sum_{n=1}^{\Gamma(t)} S_n\Theta_n\Phi_n}_{\text{undamaged}} + \underbrace{\sum_{m=1}^{K-\Gamma(t)} S_m\Theta_m\Psi_m}_{\text{damaged}} + w, \tag{8}$$

where $\Psi_m = \beta(\psi_m)\exp(-\jmath\psi_m)$, and $\psi_m \sim \mathcal{U}[0,2\pi]$ [8]. Additionally, the damaged elements are positioned randomly on the surface. It should be emphasized that $y(t)$ denotes the received signal after the total runtime t. We omit (t) in the following discussion for brevity.

Received signal power maximization: In order to maximize the received signal power, we design the phase shift set of the RIS which aims to align the direct and the cascaded links. From (5), the optimal phase shift set can be designed as [8]

$$\phi_n^{\text{opt}} = 2\pi\left\{f_c(\tau_0-\tau_n)+k_n\right\}, \tag{9}$$

where $k_n = \lceil f_c(\tau_n-\tau_0)\rceil$. Thus, the received signal power without the AWGN w can be obtained, from (8), as

$$\mathcal{Q} = \mathbb{E}\left\{\left|S_0\Theta_0 + \sum_{n=1}^{\Gamma} S_n\Theta_n\Phi_n + \sum_{m=1}^{K-\Gamma} S_m\Theta_m\Psi_m\right|^2\right\}. \tag{10}$$

Since $|\mathbb{E}\{e^{-\jmath\gamma_n}\}|^2 = \text{sinc}^2(\alpha)$, $\mathbb{E}\{|\sin(\phi_n+\gamma_n-c)+1|\} = \sin(\phi_n-c)\text{sinc}(\alpha)+1$, $\psi_m \sim \mathcal{U}[0,2\pi]$, and (ϕ_n-c) can be considered as the uniform distribution over $[-c, 2\pi-c]$, we then have

$$\mathcal{Q} \simeq A_0^2 + A_0(1+b)\text{sinc}(\alpha)\sum_{n=1}^{\Gamma} A_n + \left(\frac{1+b}{2}\right)^2 A^\star + \left(\frac{1+b}{2}\right)^2 \sum_{m=1}^{K-\Gamma} A_m^2, \tag{11}$$

where

$$A^\star \triangleq \sum_{n=1}^{\Gamma} A_n^2 + \text{sinc}^2(\alpha)\left(A_1\sum_{n\neq 1}^{\Gamma} A_n + \cdots + A_\Gamma \sum_{n\neq\Gamma}^{\Gamma} A_n\right). \tag{12}$$

From (11), we can observe that the HWI γ_n leads to two scalable factors, $\text{sinc}(\alpha)$ and $\text{sinc}^2(\alpha)$, that decrease the received signal power. Besides, the PAV results in the scalable factors $(1+b)$ and $(\frac{1+b}{2})^2$. Moreover, due to the HA effect, $(K-\Gamma)$ damaged elements decrease their gain to $(\frac{1+b}{2})^2\sum_{m=1}^{K-\Gamma} A_m^2$.

Spectral efficiency: The SE of the received signal (8) can be obtained as

$$\text{SE} = \mathbb{E}\left\{\log_2\left(1+\frac{|y(t)-\omega|^2}{\sigma^2}\right)\right\}. \tag{13}$$

Since $\mathbb{E}\{\log_2(1+\frac{x}{y})\} \simeq \log_2(1+\frac{\mathbb{E}\{x\}}{\mathbb{E}\{y\}})$ [3], we can rewrite (13) as

$$\text{SE} = \log_2\left(1+\frac{\mathcal{Q}}{\sigma^2}\right). \tag{14}$$

Hardware aging analysis: Based on the received signal power expression (11), we then compare the received power between the practical RIS and the RIS only with residual HWI to capture the impact of the HA of the RIS model on the received signal power.

Consider (11), (12), and $A_0 = 0$ (i.e. the direct link is blocked), denote $\mathcal{Q}_{\text{HA}}$ as the received signal power for the RIS with PAV, residual HWI and HA, we then have

$$\mathcal{Q}_{\text{HA}} = \left(\frac{1+b}{2}\right)^2\left(A^\star + \sum_{m=1}^{K-\Gamma} A_m^2\right). \tag{15}$$

Assuming each cascaded link has identical channel gain, that is, $A_1 = A_2 = \cdots = A_K$, and $\Gamma \gg 1$, then

$$\mathcal{Q}_{\text{HA}} \simeq \left(\frac{1+b}{2}\right)^2\left(KA_1^2 + \text{sinc}^2(\alpha)\Gamma^2 A_1^2\right), \tag{16}$$

and denote $\mathcal{Q}_{\text{HWI}}$ as the received signal power for RIS with only the residual HWI, that is,

$$\mathcal{Q}_{\text{HWI}} \simeq KA_1^2 + \text{sinc}^2(\alpha)K^2A_1^2. \tag{17}$$

Therefore, when the direct link is blocked, the received power ratio ϵ between $\mathcal{Q}_{\text{HA}}$ and $\mathcal{Q}_{\text{HWI}}$ after runtime t is

$$\epsilon = \frac{\mathcal{Q}_{\text{HA}}}{\mathcal{Q}_{\text{HWI}}} \simeq \left(\frac{1+b}{2}\right)^2 \frac{K+\text{sinc}^2(\alpha)\Gamma^2}{K+\text{sinc}^2(\alpha)K^2}. \tag{18}$$

When the RIS is not used for a long time, that is, $t \ll L$, then

$$\epsilon \to (1+b)^2/4. \tag{19}$$

This result reveals that although the RIS is without the HA, ϵ still suffers from the PAV instead of the residual HWI.

When the runtime t and lifetime L do not differ much, we have

$$\epsilon \to (\Gamma/K)^2(1+b)^2/4. \tag{20}$$

It can be observed that at this stage, the residual HWI does not affect ϵ, but the HA effect causes the impairment factor $(\Gamma/K)^2$.

When $t \gg L$, then $\Gamma \to 0$. Thus,

$$\epsilon \to \left(\frac{1+b}{2}\right)^2 \frac{1}{1+\text{sinc}^2(\alpha)K} \simeq 0. \tag{21}$$

It is worth noting that $\text{sinc}^2(\alpha)K \gg 1$, so at this runtime stage, ϵ reduces to 0, that is, the RIS loses its capability for beamforming.

Simulation results: In this section, numerical evaluations are presented to validate the results in previous sections. The following basic setup is considered by default unless otherwise specified: $f_c = 2.4$ GHz, $K = 64^2$, $dx = dy = \lambda_c/(2\sqrt{\pi})$, $a = 1$, $b = 0.2$, $c = 0.43\pi$, $\rho \in [1, 3.5]$, $P_t = 20$ dBm, $\sigma^2 = -80$ dBm, and $q = 2$. The number of realizations is 5×10^3. Besides, considering the BS, the RIS, and the user are all in the three-dimensional (3D) Cartesian coordinate system, the position for the BS is [-50 m, 15 m, 20 m]$^{\text{T}}$, the center of RIS locates at [0 m, 10 m, 0 m]$^{\text{T}}$. For the position of the user, we consider two different modes. The first one is the user moves slowly along the x-axis from [-100 m, 1.5 m, 50 m]$^{\text{T}}$ to [100 m, 1.5 m, 50 m]$^{\text{T}}$, the total moving time can be

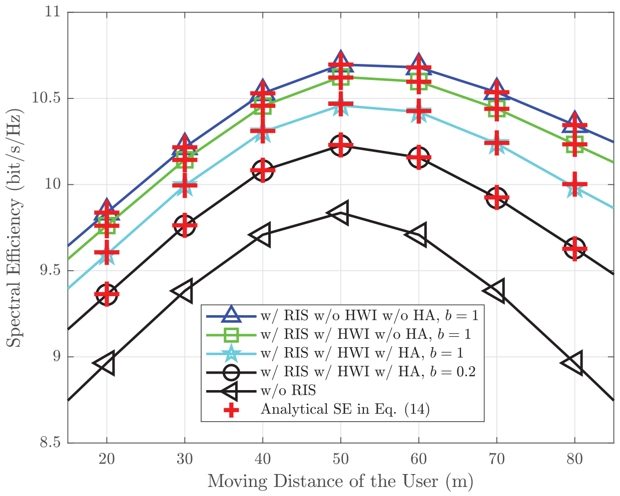

Fig. 1 *SE for the moving user.* $q = 2$, $t = 2000$ *h and* $L = 500$ *h*

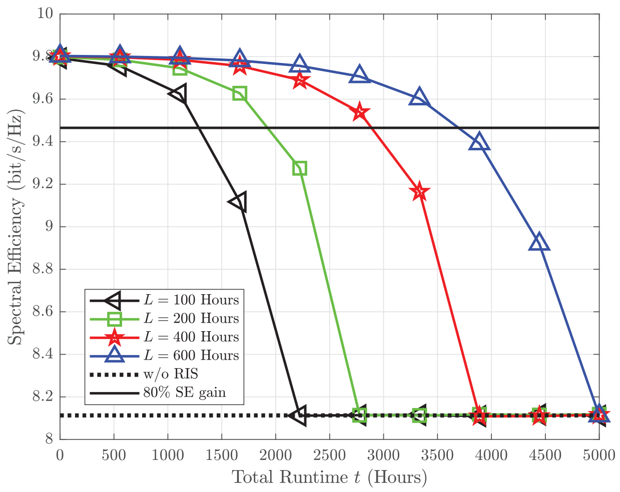

Fig. 2 *SE for different lifetimes. The RIS is with HA and without HWI.* $q = 2$, $b = 1$, *and* $t = 0, 1, \ldots, 5000$ *h*

omitted compares to the runtime t, and Doppler effect is not considered. The second one is the static user with the position $[0\text{ m}, 1.5\text{ m}, 50\text{ m}]^{\mathrm{T}}$.

Figure 1 plots the SE obtained in (14) and validates it against numerical simulations. Considering the user in the first mode, it can be seen that the ideal RIS model without the PAV, the residual HWI, or the HA, performs best, as expected; and the worst case is the practical RIS with HWI and HA. When the moving distance is 50 m, all cases are with the highest SE. This is because the direct link gain A_0 in (6), which depends on d_0 and λ_c, is the largest at this time. Similarly, the cascaded link gain A_n in (7) can be calculated using d_{1n}, d_{2n}, and λ_c. The analytical results match well with the simulated results. Therefore, we use (11) and (14) to generate results for Figures 2 to 5.

As shown in Figure 2, the HA effects on the RIS with different lifetimes. Consider the user is in the second mode. It can be seen that the RIS with $L = 100$ h performs the worst, as expected. Specifically, after 2223 hs of operation, the SE reduced from 9.80 to 8.11 bit/s/Hz. Besides, when the runtime t is smaller than or equal to the lifetime, the HA effect is insignificant to the overall system performance. The insight reveals that we should pay more attention to the HA effect when the RIS has been used for a long time. In addition, the long-term durability of RIS is evident. For example, when $L = 200$ and $t = 1800$ h, the RIS only loses 20% of its SE gain, that is, from 9.8 to 9.47 bit/s/Hz.

With different b, Figure 3 shows the performance degradation caused by the practical RIS. It can be observed that the PAV would cause SE loss. However, if the runtime t is long enough, then the HA effect, instead of the PAV, would dominate the whole impairment.

Figure 4 illustrates the SE loss by different residual HWI γ_n. It can be seen that the residual HWI decreases the system performance. Besides,

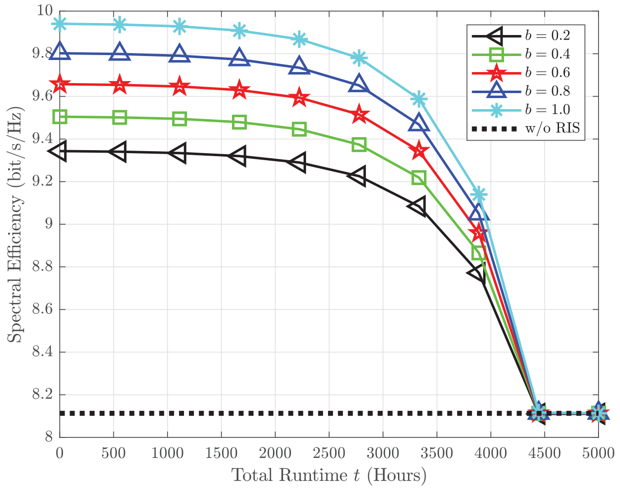

Fig. 3 *SE for different* b*. The practical RIS is with HA but without HWI.* $q = 2$, $t = 0, 1, \ldots, 5000$ *h, and* $L = 500$ *h*

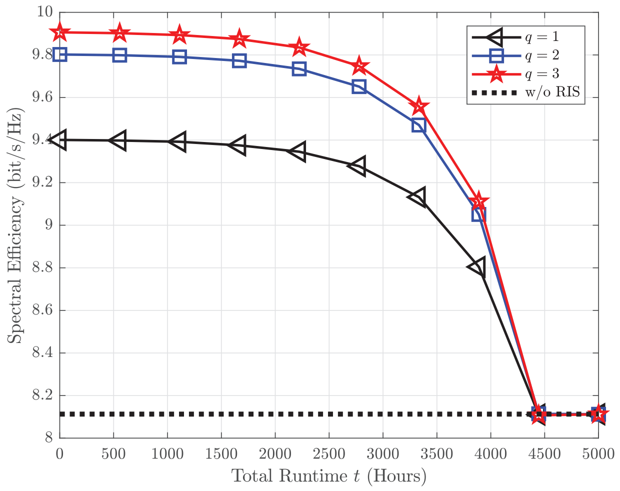

Fig. 4 *SE for different HWI.* $\gamma_n \sim \mathcal{U}[-\alpha, \alpha]$*, where* $\alpha = 2^{-q}\pi$. $b = 1$, $t = 0, 1, \ldots, 5000$ *h, and* $L = 500$ *h*

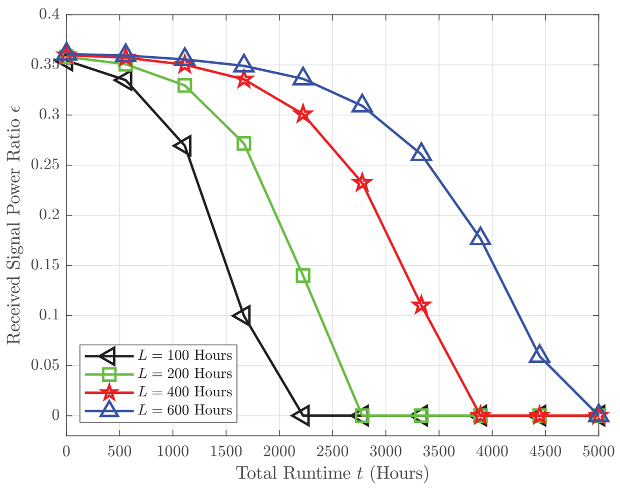

Fig. 5 *Received signal power ratio* ϵ. $q = 2$, $b = 0.2$, $t = 0, 1, \ldots, 5000$ *h.*

similar to the PAV, γ_n would not be the main impairment factor when the runtime t is long enough.

Figure 5 validates (19) (20) and (21). In particular, when $t \ll L$, the PAV is the main impairment factor. When the runtime t increases, ϵ decreases because of the HA effect, as expected. When $t \gg L$, the RIS becomes a random scatter since all elements are with random phase shifts. $L = 100$ and $L = 600$ h are the best and worst cases, as expected.

Conclusion: In this letter, we have introduced the HA effect on the practical RIS-assisted communication system. Asymptotic analysis and numerical evaluations showed that the HA effect is the main impairment factor when the runtime is long enough. HA analysis considering the impact of small-scale fading are left open for future works.

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