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How Long Can RIS Work Effectively: An Electronic Reliability Perspective

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Outline

- Part 1: Introduction and Major Contributions
- Part 2: System Model
- Part 3: Stochastic Hardware Aging Effects on RIS
- Part 4: Simulation Results
- Part 5: Conclusion and Future Works

Part 1: Introduction and Major Contributions

RIS: A Promising Technology in B5G/6G

- Reconfigurable intelligent surface (RIS) is a planar surface that is made up of massive sub-wavelength passive reflectors, each of them causing amplitude and/or phase shifts on the incident electromagnetic wave independently and instantaneously.

- The RIS can help enhance transmission coverage, localization, and mitigate the Doppler effect, etc.

- By utilizing the RIS, it is possible to reorient the reflected signal for improving transmission performance in B5G/6G.

- However, some practical impairment factors (IF) of the RIS-aided system should be considered.

Previous works have shown that there are three conventional IFs in the RIS system.

Traditional Practical Impairment Factors of the RIS-aided System

- **Residual IF in RIS elements (RIF): caused by intrinsic hardware imperfections and channel estimation errors, can be modeled as uniform random phase errors such as** $\gamma \sim \mathcal{U}[-\alpha, \alpha]$, **where** $\alpha \triangleq 2^{-q}\pi,\ q \geq 1$.

- **Residual IF in transceivers (TIF): caused by imperfect modeling and distortion, can be modeled as complex Gaussian noise** $\eta \sim \mathcal{CN}(0, V)$.

- **Phase-dependent amplitude variations (PAV): caused by the nonlinear relationship between the RIS phase shift and its amplitude, i.e.,**

$$\beta(\phi) = (1-b)\left(\frac{\sin(\phi - c) + 1}{2}\right)^a + b,\ a, b, c \geq 0.$$

Do we have non-residual IF in the RIS-aided system?

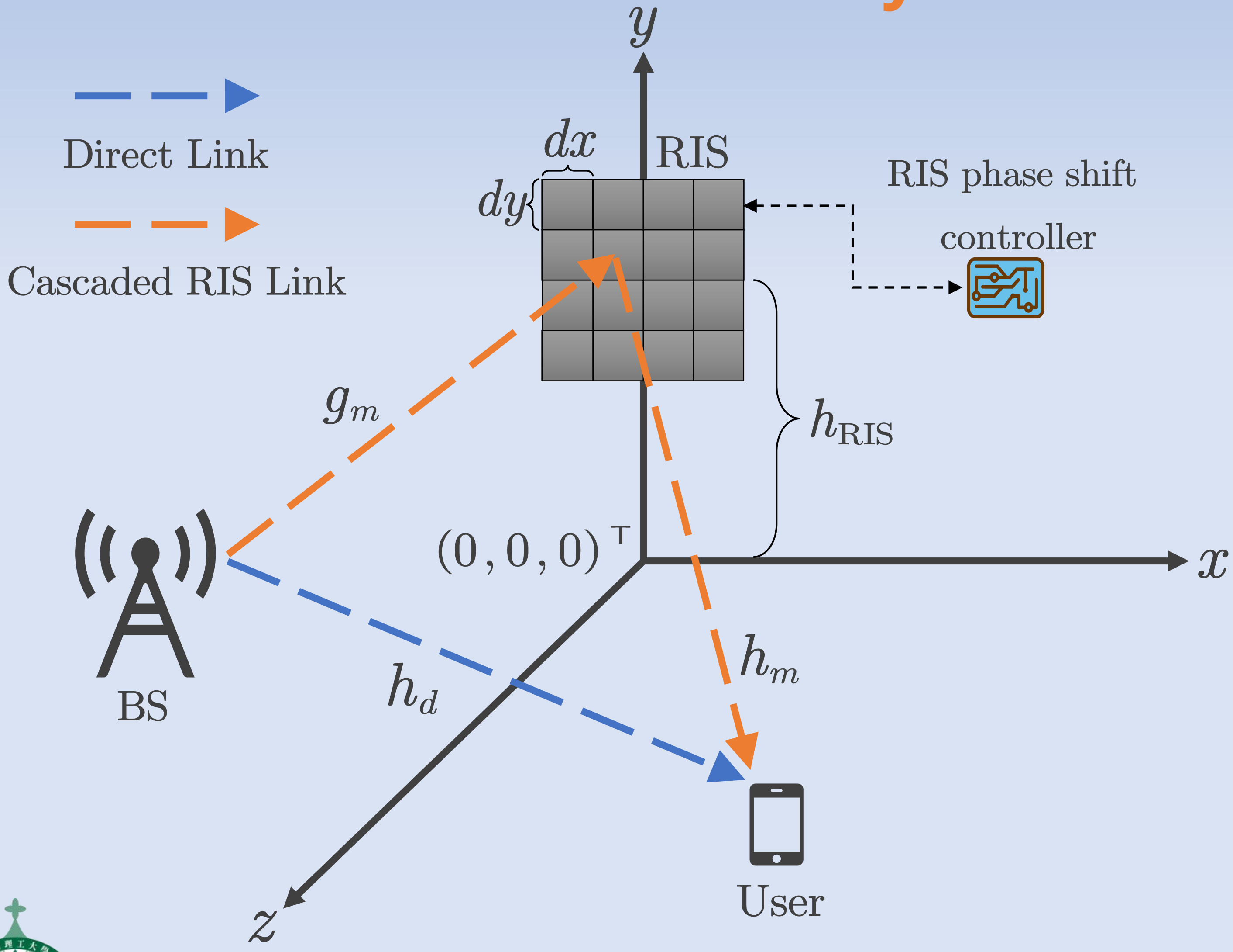
Insight: When the RIS is far away from the BS (user), the RIF dominates, otherwise the TIF is more important. The three IFs above are all residual.

Major Contributions in This Work

- Firstly, we introduce a new non-residual IF of the RIS, i.e., the stochastic hardware aging (HA) effect, to describe runtime-related hardware degradations and failures.
- Secondly, we mathematically show that the lifetime of the RIS is the runtime that 63.2% of elements fail.
- Besides, we propose a Rician near-field 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.
- Lastly, we show that the stochastic HA effect, rather than the other residual IFs, is the main degradation cause when the runtime is beyond the lifetime. We also obtain the closed-form achievable rate of the proposed model.

Part 2: System Model

The Near-Field RIS System Model with Residual IFs



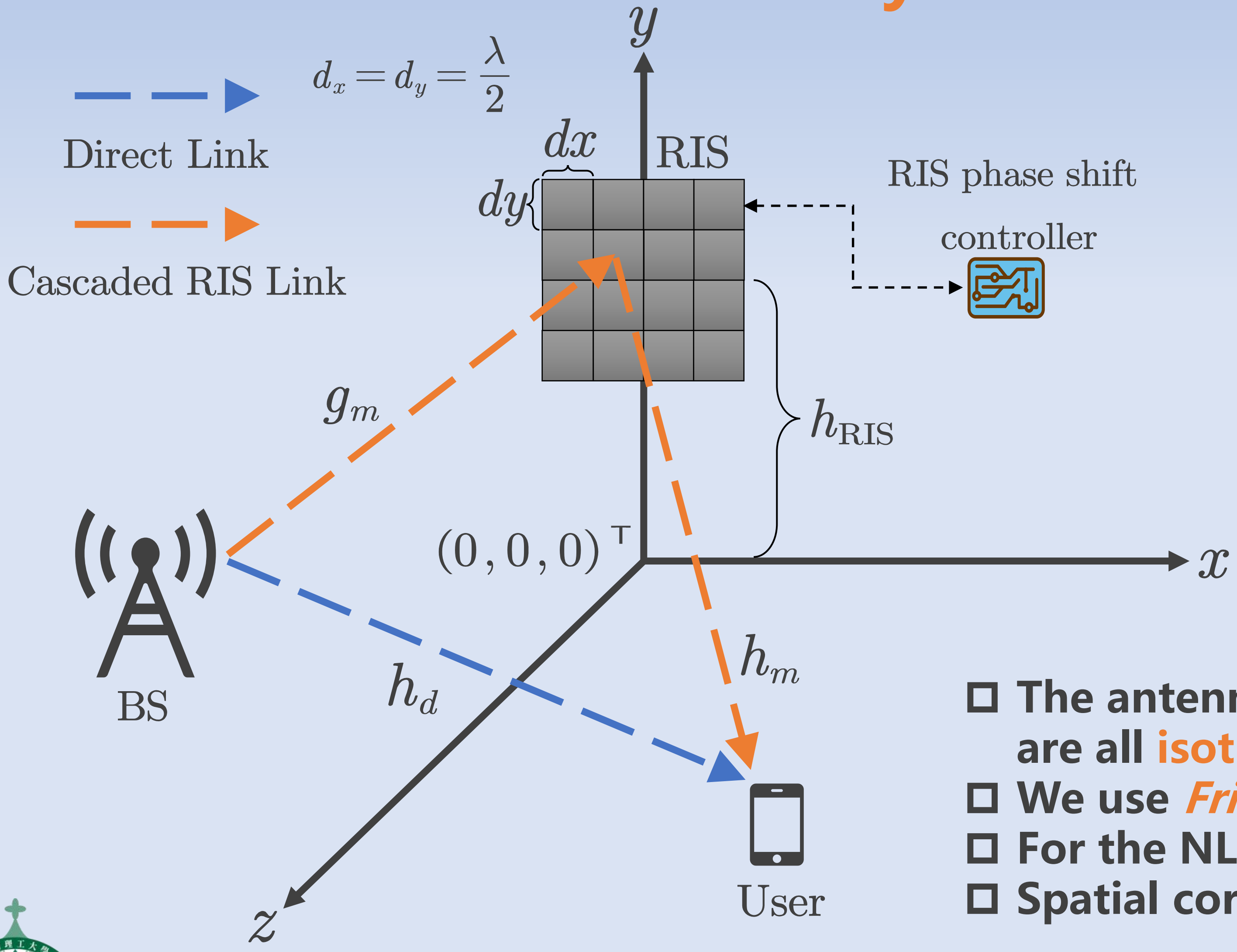
$$h_d = A_0\left(\sqrt{\frac{\kappa_d}{\kappa_d+1}}\, h_d^{\mathrm{LoS}} + \sqrt{\frac{1}{\kappa_d+1}}\, h_d^{\mathrm{NLoS}}\right).$$

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

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

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

The Near-Field RIS System Model with Residual IFs



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

$$\psi_m = \beta(\phi_m + \gamma_m)\exp(-\jmath(\phi_m + \gamma_m))$$

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

- The antennas of the transceiver and the RIS element are all **isotropic**.
- We use ***Friis Transmission Equation*** in the LoS link.
- For the NLoS parts, $h_d^{\text{NLoS}}, g_m^{\text{NLoS}}, h_m^{\text{NLoS}} \sim \mathcal{CN}(0,1)$.
- Spatial correlation is ignored in this paper.

Part 3: Stochastic Hardware Aging Effects on RIS

Stochastic Hardware Aging Effects

- Stochastic HA effects mainly denote the growth of runtime-related random failures (damages) for the RIS elements. It is caused by multiple reasons such as aging of electronic circuit, extreme weather, etc.

- In terms of the total runtime t, the probability density function (PDF) of the failure rate for one single RIS reflector is characterized by ***Weibull distribution***. The PDF can be obtained as

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

t is not the instantaneous time but the accumulative runtime of the RIS-aided system.

where $L\geq 0$ is the expected lifetime of the RIS element, and $\rho\in[1,\ 3.5]$ is the empirical shape parameter.

Besides, the element failure would cause $\phi\sim\mathcal{U}[0,2\pi]$ and $\beta\sim\mathcal{U}[0,1]$.

Proposition 1

- Consider an RIS with M elements, and after runtime t, **the expected number of undamaged elements** is

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

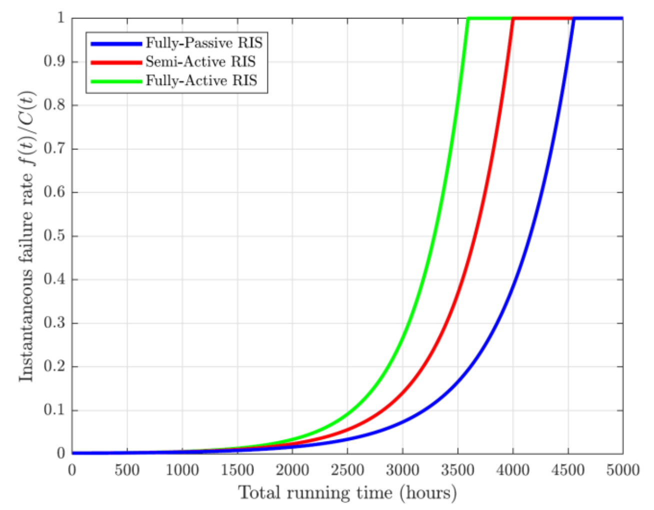
where μ is **early external failure rate (i.e., probability of manufacturing errors)**.

- Proof: Please see the paper for details.

- Different types of RIS have different parameter ρ and μ.

A device is easier to fail if it works with a stronger current.

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



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 can be obtained as**

$$C(t) = 1 - \int_0^t f(t)\,dt = \text{exp}(-\frac{t}{L}) = \text{exp}(-1) = 0.368.$$

Hence the number of expired elements is about 63.2%.

Insight: Proposition 2 provides a threshold that determines an intelligent surface is "healthy" or not. This can be further investigated in the future.

The Near-Field RIS System Model with the HA effect

- 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 $S(t)=M-N(t)$, and the total channel expression h can be rewritten as

$$\bar{h}(t)=h_d+\boxed{\sum_{n=1}^{N(t)} h_n \psi_n g_n}+\boxed{\sum_{s=1}^{S(t)} h_s \bar{\psi}_s g_s}.$$

- Special Case: When the t is long enough, $N(t)=0$ and $S(t)=M$, then the RIS becomes a random scatterer. Accordingly, the received signal at this time can be obtained as

$$\bar{y}(t)=h_d+\sum_{s=1}^{S(t)=M} h_s \bar{\psi}_s g_s(\sqrt{P}x+\eta_t)+\eta_r+\omega.$$

Insight: When considering practical RIS implementations, the lifetime of the RIS should be considered. The RIS degrades to a random scatterer eventually.

Part 4: Simulation Results

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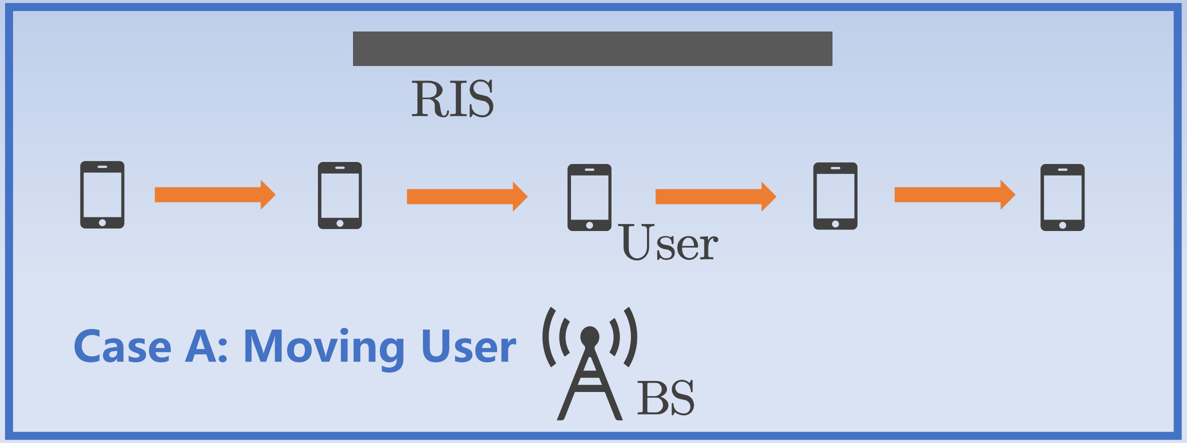
Parameters Setting



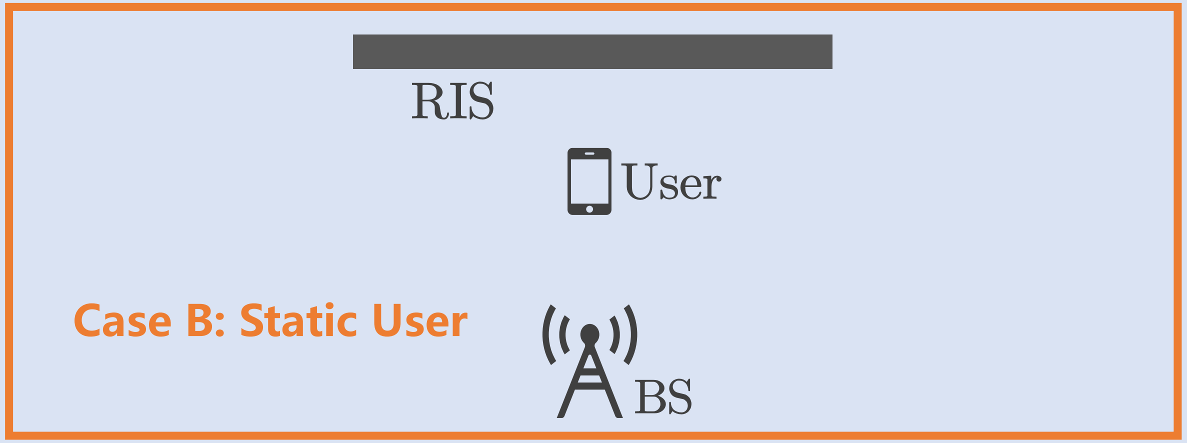
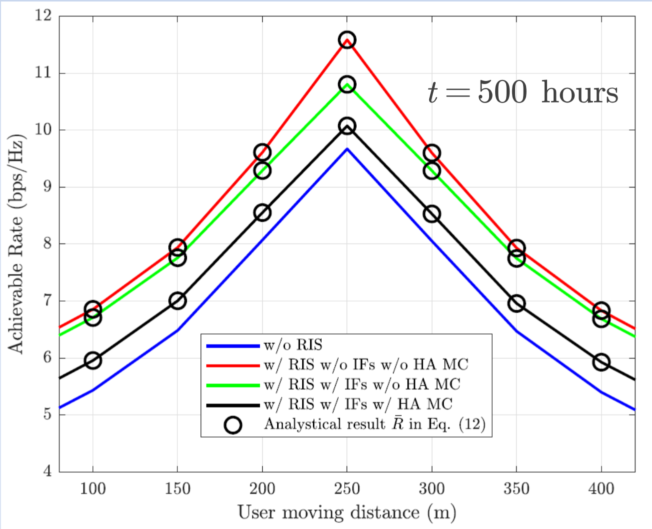


TABLE II
SIMULATION PARAMETERS

Parameters	Values
Position of the BS (D_{BS})	$[0\text{ m}, 20\text{ m}, 50\text{ m}]^{\mathsf{T}}$
Position of the user (D_{user})	$[0\text{ m}, 2\text{ m}, 20\text{ m}]^{\mathsf{T}}$ / moving
Position of the $n(s)$-th element ($D_{\mathrm{n(s)}}$)	See Eq. (1) in [9]
The center of RIS	$[0\text{ m}, 15\text{ m}, 0\text{ m}]^{\mathsf{T}}$
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

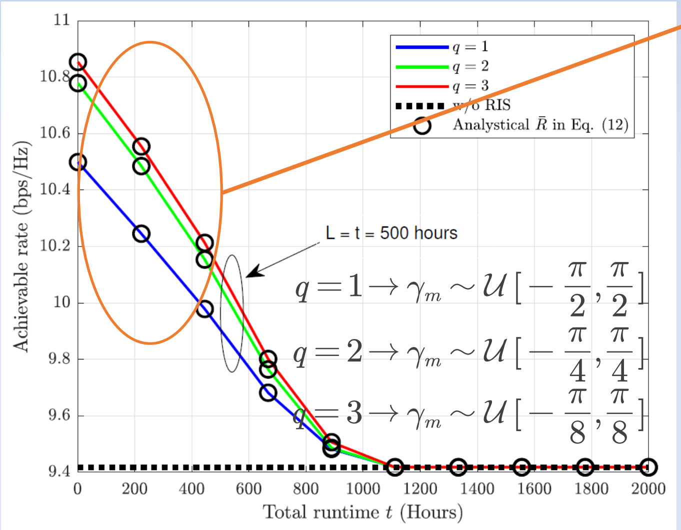
Simulation Results

Case A: Moving User

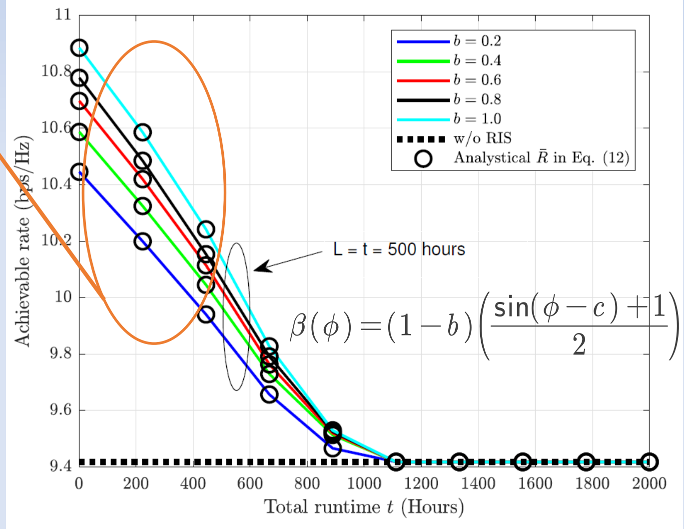


Case B: Static User

Previous works focused on.



Case B: Static User



Achievable Rate: $R(t) = \mathbb{E}\left\{\log_2\left(1 + \frac{P|\bar{h}(t)|^2}{P(\iota_t + \iota_r)|\bar{h}(t)|^2 + \sigma^2}\right)\right\} \approx \log_2\left(1 + \frac{PQ(t)}{P(\iota_t + \iota_r)Q(t) + \sigma^2}\right)$

See the paper for more details.

Insight: for Case A, if the HA is ignored, the TIF dominates when the user near the BS (the RIS). However, if consider the HA, the RIF and the TIF are not important.

Insight: for Case B, the different residual IFs have different impacts when $t < L$, otherwise the HA dominates.

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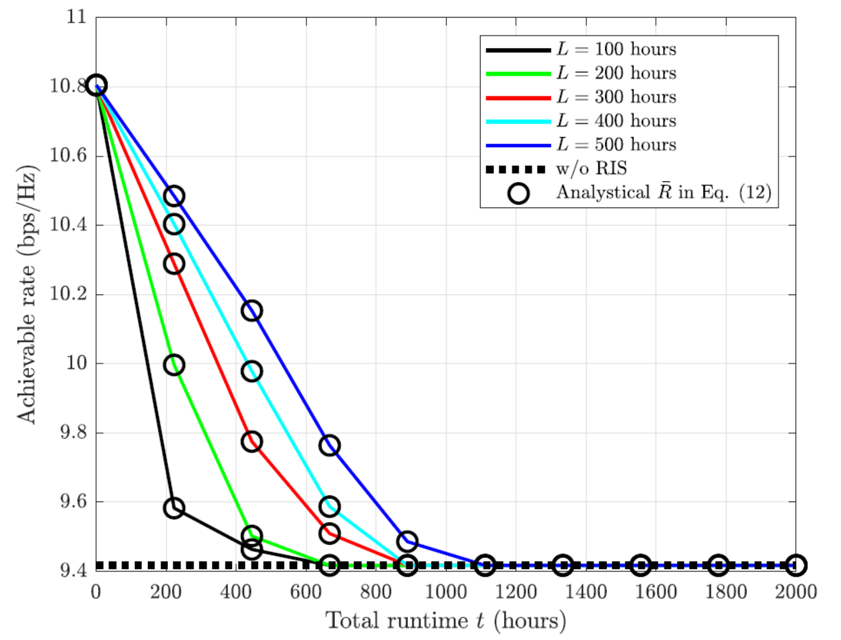
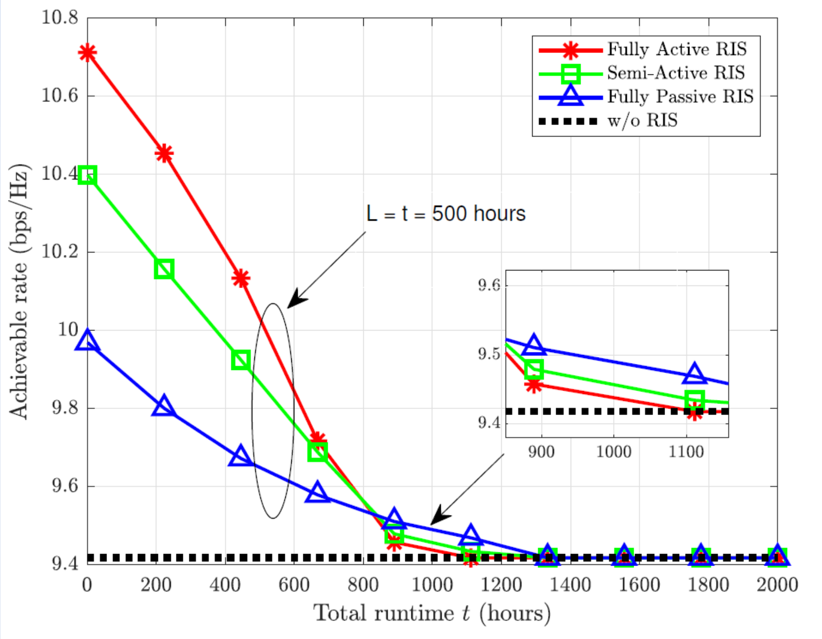
Simulation Results

Case B: Static User



Case B: Static User



Insight: different lifetimes would cause different performances when $t > 0$.

Insight: Since the active RIS element works with stronger currents, it is more fragile. Thus, when the runtime is beyond the lifetime, the fully passive RIS may provide a longer performance enhancement.

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Part 5: Conclusion and Future Works

Conclusion and Future Works

- Previous studies only discussed the residual IFs, which is not practical enough. Our work introduced a new non-residual IF, i.e., the HA effect, to describe the degradation behavior when the runtime is long enough.

- We mathematically defined that the lifetime of the RIS is the runtime that 63.2% of elements fail. This important threshold divides the life cycle of the RIS system into two phases, i.e., $t < L$ and $t \geq L$.

- This paper can be regarded as a guideline for predicting and evaluating the whole life cycle performance of the RIS-aided system.

- Measuring practical reliability parameters via RIS hardware and how to compensate for the non-residual IFs are left open for future works.

Thank You

Q&A?