On Hardware Aging for Practical RIS-Assisted Communication Systems

Ke Wang, Chan-Tong Lam and Benjamin K. Ng

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, we obtain a practical RIS-assisted system model with phase-dependent amplitude variations, residual hardware impairments, and HA effects. Besides, we derive closed-form expressions of the received signal power and spectral efficiency for the proposed system. 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, quantization error, *et al*. limit the system performance [3, 4]. Xing *et al*. [3] considered the HWI 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 operation. 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 first use Weibull distributions to model the HA effect for the runtime of the RIS. Then, a practical RIS model with the PAV, the HWI, and the HA effect is obtained. We derive closed-form expressions of the received signal power and the SE. Besides, analytical analysis and simulation results unveil that the RIS performance is limited not only by the HWI but also by the PAV and the HA. More importantly, as the runtime grows, the HA effect becomes more severe. 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 $n = 1, \ldots, K$, 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) compares 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 modeled 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].

Hardware aging 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

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

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, i.e., 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

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

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 modeled as $\beta(\phi_n)$ in (2) and the residual RIS HWI is modeled as γ_n, where $n = 1, \ldots, K$. Let's consider first the received 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 AWGN noise 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, 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

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

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

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

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]

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

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

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

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 $(\phi_n - c)$ can be considered as the uniform distribution over $[-c, 2\pi - c]$, we then have

$$\mathcal{Q} \simeq A_0^2 + A_0(1+b)\text{sinc}(\alpha) \sum_{n=1}^{\Gamma} A_n$$

$$+ (\frac{1+b}{2})^2 A^\star + (\frac{1+b}{2})^2 \sum_{m=1}^{K-\Gamma} A_m^2, \qquad (11)$$

where

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

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

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

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

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

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
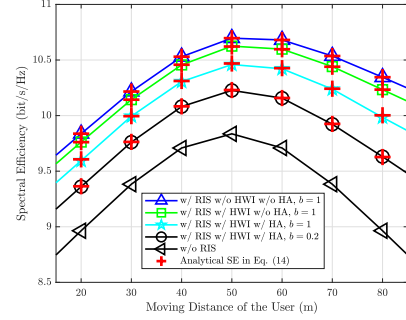

Fig. 1. SE for the moving user. $q = 2$, $t = 2000$ hours and $L = 500$ hours.

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

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

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

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

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

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

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

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

$$\epsilon \to (1+b)^2/4. \qquad (19)$$

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

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

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

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

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

It is worth noting that $\text{sinc}^2(\alpha)K \gg 1$, so at this runtime stage, ϵ reduces to 0, i.e., 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 $[-50\text{ m}, 15\text{ m}, 20\text{ m}]^\text{T}$, the center of RIS locates at $[0\text{ m}, 10\text{ m}, 0\text{ m}]^\text{T}$. For the position of the user, we consider two different modes. The first one is the user moves slowly along the x-axis from $[-100\text{ m}, 1.5\text{ m}, 50\text{ m}]^\text{T}$ to $[100\text{ m}, 1.5\text{ m}, 50\text{ m}]^\text{T}$, the total moving time can be omitted compares to the usage time t, and Doppler effect is not considered. The second one is the static user with the position $[0\text{ m}, 1.5\text{ m}, 50\text{ m}]^\text{T}$.

Fig. 1 plots the SE obtained in (14) and validates against numerical simulations. Consider 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. In particular, 10.70 bit/s/Hz, 10.23 bit/s/Hz, and 9.84 bit/s/Hz are obtained
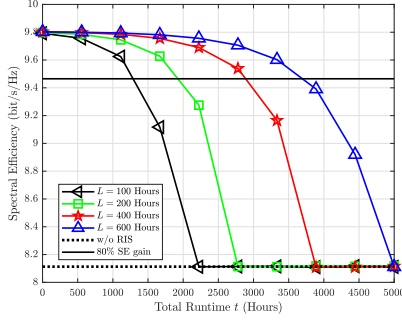
Fig. 2 *SE for different lifetimes. The RIS is with HA and without HWI. $q = 2$, $b = 1$, and $t = 0, 1, \ldots, 5000$ hours.*
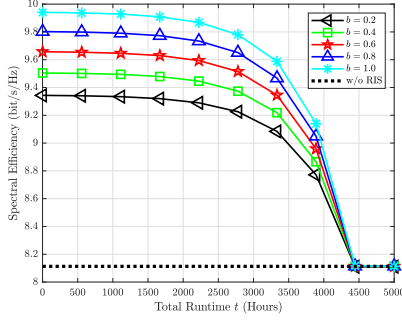

Fig. 3 *SE for different b. The practical RIS is with HA but without HWI. $q = 2$, $t = 0, 1, \ldots, 5000$ hours, and $L = 500$ hours.*

for the ideal RIS model without any degradation, the practical RIS model with HWI and HA, and without RIS case, respectively. 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 Fig. 2 to Fig. 5.

As shown in Fig. 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 $L = 100$ hours performs the worst, as expected. Specifically, after 2223 hours 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 $t = 1800$ hours, the RIS only loses 20% of its SE gain, i.e., from 9.8 to 9.47 bit/s/Hz.

With different b, Fig. 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.
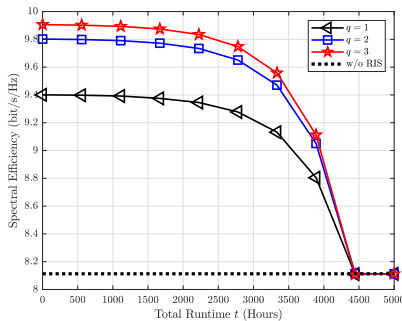

Fig. 4 *SE for different HWI. $\gamma_n \sim \mathcal{U}[-\alpha, \alpha]$, where $\alpha = 2^{-q}\pi$. $b = 1$, $t = 0, 1, \ldots, 5000$ hours, and $L = 500$ hours.*
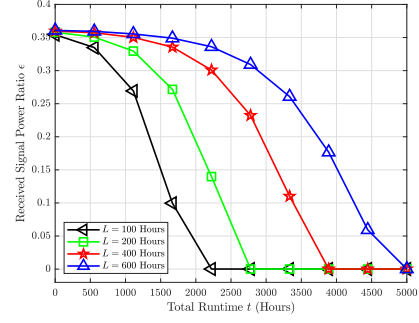

Fig. 5 *Received signal power ratio ϵ. $q = 2$, $b = 0.2$, $t = 0, 1, \ldots, 5000$ hours.*

Fig. 4 illustrates the SE loss by different residual HWI γ_n. It can be seen that the residual HWI decreases the system performance. Besides, similar to the PAV, γ_n would not be the main impairment factor when the runtime t is long enough.

Fig. 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 decrease 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 $L = 600$ hours are the best and worst cases, as expected.

Conclusion: In this Letter, we have introduced the novel model of the runtime-related HA effect on the RIS. Besides, runtimes and lifetimes have been also proposed as two parameters to describe the RIS hardware degradation. Asymptotic analysis and numerical evaluations showed the HA effect is the main impairment factor when the runtime is long enough. How to diagnose and compensate for the HA effect and HA analysis considering the impact of small-scale fading are left open for future works.

Ke Wang, Chan-Tong Lam and Benjamin K. Ng (*Faculty of Applied Sciences, Macao Polytechnic University, Macao, People's Republic of China*)

E-mail: ctlam@mpu.edu.mo

References

1 E. Björnson, H. Wymeersch, B. Matthiesen, P. Popovski, L. Sanguinetti and E. de Carvalho.: 'A Reconfigurable Intelligent Surfaces: A signal processing perspective with wireless applications', *IEEE Signal Process. Mag*, 2022, **39**, (2), pp. 135-158

2 C. Huang, A. Zappone, G. C. Alexandropoulos, M. Debbah, and C. Yuen.: 'Reconfigurable intelligent surfaces for energy efficiency in wireless communication', *IEEE Trans. Wirel. Commun*, 2019, **18**, (8), pp. 4157–4170

3 Z. Xing, R. Wang, J. Wu, and E. Liu.: 'Achievable rate analysis and phase shift optimization on intelligent reflecting surface with hardware impairments', *IEEE Trans. Wirel. Commun*, 2021, **20**, (9), pp. 5514–5530

4 S. Zhou, W. Xu, K. Wang, M. Di Renzo, and M.-S. Alouini.: 'Spectral and Energy Efficiency of IRS-Assisted MISO Communication With Hardware Impairments', *IEEE Wirel. Commun. Lett*, 2020, **9**, (9), pp. 1366-1369

5 S. Abeywickrama, R. Zhang, Q. Wu, and C. Yuen.: 'Intelligent reflecting surface: Practical phase shift model and beamforming optimization', *IEEE Trans. Commun*, 2020, **68**, (9), pp. 5849-5863

6 F. Costa and M. Borgese.: 'Circuit Modelling of Reflecting Intelligent Surfaces', *2021 IEEE 22nd International Workshop on Signal Processing Advances in Wireless Communications (SPAWC)*, 2021, pp. 546-550

7 P. O'Connor and A. Kleyner.: 'Practical reliability engineering', *John Wiley & Sons*, 2012

8 K. Wang, C.-T. Lam, and B. K. Ng.: 'Doppler effect mitigation using reconfigurable intelligent surfaces with hardware impairments', *2021 IEEE Globecom Workshops (GC Wkshps)*, 2021, pp. 1-6

9 Sun, R., Wang, W., Chen, L., Wei, G. and Zhang, W.: 'Diagnosis of Intelligent Reflecting Surface in Millimeter-wave Communication Systems', *IEEE Trans. Wirel. Commun*, 2021, **21**, (6), pp. 3921-3934

10 H. Taghvaee, A. Cabellos-Aparicio, J. Georgiou, and S. Abadal.: 'Error analysis of programmable metasurfaces for beam steering', *IEEE J. Emerg. Sel. Top. Circuits Syst*, 2020, **10**, (1), pp. 62–74

11 V. Arun and H. Balakrishnan.: 'RFocus: Beamforming using thousands of passive antennas', *Proc. 17th USENIX Symp. Netw. Syst. Design Implement (NSDI)*, 2020, pp. 1047–1061.