Outage Probability Analysis of RIS-assisted Wireless Powered Multi-user Communications

Shuying Lin, Yulong Zou, Jia Zhu, Haiyan Guo, Bin Li, and Fei Xie
School of Telecomm. and Inform. Eng., Nanjing Univ. Posts & Telecomm., Nanjing, P. R. China
*Corresponding author: Jia Zhu (email: christina825@163.com)

2021 13th International Conference on Wireless Communications and Signal Processing (WCSP) | 978-1-6654-0785-4/21/$31.00 ©2021 IEEE | DOI: 10.1109/WCSP52459.2021.9613340

Abstract—**This paper investigates the outage performance of reconfigurable intelligent surface (RIS)-assisted wireless powered multi-user communication networks (WPMCNs) consisting of a base station (BS), an RIS, multiple users as well as a power beacon (PB). Depending on the availability of wireless channel state information (CSI) in the RIS-aided networks, we propose two energy-harvesting (EH) user scheduling schemes, namely the time switching (TS) based round-robin scheduling (TS-RRS) and the TS based maximum capacity scheduling (TS-MCS) scheme. By leveraging the central limit theorem (CLT) approximation, we derive closed-form outage probabilities (OPs) for the two schemes, based on which their OPs are further minimized through the optimization of TS allocation ratio in the WPMCN. Our numerical evaluations demonstrate that obvious outage benefit from large number of independent reflectors is observed in the TS-MCS scheme of the RIS-aided WPMCNs. Moreover, the outage performance of RIS-aided WPMCNs can be notably improved by proper joint design of information and energy transmission.**

Index Terms—**Reconfigurable intelligent surface, multi-user communication, energy-harvesting, outage probability.**

I. Introduction

A. Background Works

To meet the exponentially increasing demand of users [1], opportunistic scheduling of energy-harvesting (EH) users has become a increasingly crucial technique, which has been thoroughly investigated in prior works. EH, a paradigm to prolong the working period of battery-less wireless networks, enables wireless devices to capture energy from the surrounding environment. Generally speaking, the practical receiver designs of EH can be classified as time switching (TS) and power splitting (PS) [2]. With the former TS, the receivers exploit a simple switch to divide the transmission time, performing information and energy transmission separately, which is the protocol applied by us. The latter PS concentrates on the utilization of a power splitter to separate a received signal into two parts for the EH and signal decoding. Specifically, based on the TS, the authors of [3] investigated the cooperation of two users, and analyzed the spectrum efficiency during the EH phase in the wireless powered communication network (WPCN).

Thanks to the recent advance of meta-materials, the nearly passive reflecting device reconfigurable intelligent surfaces (RISs) with many backscatter units integrated, have gained unprecedented interest in both academic and industrial communities [4]-[6]. The RIS-aided networks with relatively low power consumption can be powered by harvested energy. Combining the energy benefits of both technologies, the authors of [6] explored an RIS-aided multiple access network, where information users (IUs) and energy users (EUs) were both serviced at access points. For EUs, under the interference from the IUs, their received energies were maximized by jointly optimizing active and passive beamforming. Besides, the trade-off between data rate and energy efficiency was also studied in [6].

Conventional opportunistic scheduling based on channel state information (CSI) improves outage performance of the multi-user systems at the cost of higher equipment expanses (e.g. backhaul overhead, radio frequency chains, etc.), while to some extent, the RIS-aided multi-user networks tackle the problem by reducing overhead and inter-user interference. In the RIS-assisted multi-user system of [7], user scheduling in the scenario of both with CSI and lack of CSI were presented, then ergodic capacity and multi-user diversity gain were derived by means of Central Limit Theorem (CLT) approximation, which allows the compound sum or product of independently identically distributed (i.i.d.) variables in large numbers to be approximated as a Gaussian variable. As the reflecting elements number grows, the CLT can be applied in performance analysis on RISs. The authors of [8] evaluated the performance of RIS-assisted systems with accurate channel distributions, where the outage probabilities (OPs) have not only been given by CLT approximation, but also in closed forms by the K_G distribution in the form of the Meijer G-function, which is a special kind of Nakagami-m fading distribution and has been used to characterize MIMO channels. However, due to the computation complexity of K_G distribution itself, few further theoretical researches have been conducted following [8] above.

B. Motivation and Our Contributions

So far, although a promising future is foreseen, the RIS-assisted outage performance is still understudied, particularly for RIS-aided wireless powered multi-user communication networks (WPMCNs). Inspired by the above research gap, we conduct works in this paper whose main contributions are summarized as the following:

We propose the TS based round-robin scheduling (TS-RRS) and the TS based maximum capacity scheduling (TS-MCS) schemes in an RIS-aided WPMCN, and derive the theoretical

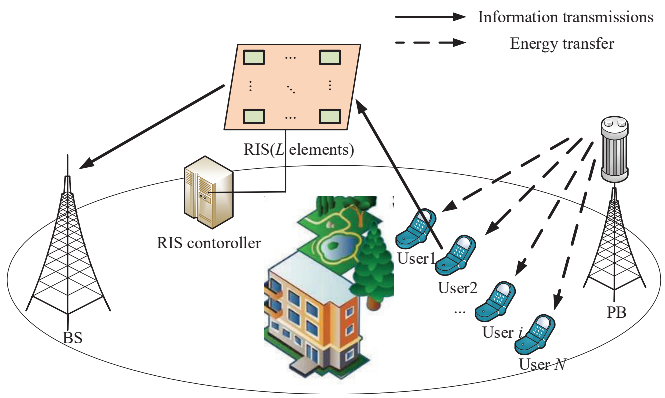

Fig. 1. An RIS-aided WPMCN.

OP expressions of both schemes. Additionally, based on these closed-form OP analysis, we give the time slot partitions between information transmission and energy transfer.

C. Outline

The rest of the paper is organized as follows. Section II describes the system model of an RIS-aided WPMCN. In Section III, we derive closed-form OPs for the TS-RRS and TS-MCS schemes, respectively, and the EH optimal time splitting fraction is obtained to minimize the OPs as well. Next, numerical results of the outage performance are provided in Section IV. Finally, some concluding remarks are drawn in Section V.

II. System Model of RIS-aided wireless powered multi-user communication networks

In this paper, we investigate an RIS-aided WPMCN consisting of one base station (BS), an RIS with L low-cost passive reflecting elements, N energy-aware users each equipped with a single antenna, as illustrated by Fig. 1, and all EH user terminals share a power beacon (PB) nearby. The transmission time of all links falls within a coherence interval of the channels so that all channels are supposed to experience quasi-static flat-fading.

A. Energy Harvesting Process

All user terminals rely on the PB as wireless power supplies in a terrestrial network whose links are dominated by NLoS components, so the channels for users to acquire energy from the PB are modeled as zero-mean complex Gaussian random variables h_{iP} with variances of σ_{iP}^2. Then the magnitudes of the fading follow Rayleigh distribution, and the $|h_{iP}|^2$ is exponentially distributed with a mean of σ_{iP}^2. Specifically, the PB first broadcasts wireless energy to all users in βT, where $0 < \beta < 1$ is the time allocation ratio and T is the time duration of a slot. A linear EH model is used, while other nonlinear EH model can be considered likewise, therefore the energy harvested by the i-th user in the first phase is given by

$$E_i = \eta \beta T P_b \left| h_{iP} \right|^2, \tag{1}$$

where $0 < \eta < 1$ denotes the efficiency of energy conversion and P_b denotes the fixed-amount transmit power of the PB shared by all user terminals, β denotes the same time allocation ratio for every user. It needs to be pointed out that here we assume the i users all make full use of the EH period individually to harvest energy from the PB, wherein $i \in \{1, \cdots, N\}$. Then, the users utilize the energy to transmit information in its own time slot at the remaining $(1-\beta)T$. Hence, the transmit power of the i-th user is described as

$$P_i = \frac{\eta \beta P_b \left| h_{iP} \right|^2}{1-\beta}. \tag{2}$$

B. Information Transmission Process

As can be seen from Fig. 1, the RIS is connected to a smart RIS controller, which not only receives control signals from the BS so as to optimize the reactions of its each reflector, but also forward the CSI of the link from users to RIS back to the BS [9]. We assume direct link transmissions from the users to the BS is seriously blocked, leading to the communication outage in conventional non-RIS networks. Exploiting the RIS's control of wireless environment (e.g. propagation path), the advantageous position (e.g. in the air) of the RIS makes LoS propagation components available for the reflective links both from the BS to the RIS and from the RIS to the users. Thus the reflective links fading are modeled as non-zero-mean complex Gaussian variables with variances of σ_{iR}^2 and σ_{RB}^2. Then the practical fading channels with magnitudes following Rician distribution are characterized as

$$\mathbf{h}_l = \sqrt{\frac{K_l}{K_l+1}} \overline{\mathbf{h}}_l + \sqrt{\frac{1}{K_l+1}} \tilde{\mathbf{h}}_l, \tag{3}$$

where the subscripts l denotes two different channels, $l \in \{iR, RB\}$ represent that from the RIS to the users and from the BS to the RIS, respectively. The $\overline{\mathbf{h}}_l$ with overlines denotes the deterministic components, and the $\tilde{\mathbf{h}}_l$ with curly overlines denotes the random scattered components modeled by complex Gaussian distribution with means of zero and variances of σ_{iR}^2 or σ_{RB}^2. To be specific, all L reflectors of this RIS are co-located, while the scenario of distributed RIS units is beyond the scope of this paper. Thus, for vectors $\mathbf{h}_{iR}$ and $\mathbf{h}_{RB}$, different elements within are assumed as i.i.d. distributions. The K_l denotes the Rician factor, a parameter used to describe the weight of line-of-sight/non-line-of-sight (LoS/NLoS) components are zero-mean complex Gaussian variables components.

We consider the uplink data transmission scenario, as illustrated by Fig. 1, then in the second phase of information transmission, when the i-th user ($i \in \{1, ..., N\}$) sends its normalized signal x_i (satisfying $E[|x_i|^2] = 1$) at its stored power of P_i, the received signal at the BS can be written as

$$y_{iB} = \sqrt{P_i} \left({\mathbf{h}_{iR}}^T \boldsymbol{\theta}_i \mathbf{h}_{RB} \right) x_i + n_B, \tag{4}$$

where complex-valued vectors $\mathbf{h}_{iR} \in C^{N \times 1}$, $\mathbf{h}_{RB} \in C^{N \times 1}$ represent the channel fading coefficients of the two-hop reflective links, respectively, with vectors expressed as $\mathbf{h}_{iR} = [h_{iR_1}, h_{iR_2}, h_{iR_n}, \cdots, h_{iR_L}]^T, \mathbf{h}_{RB} =$

$[h_{R_1B}, h_{R_2B}, h_{R_nB}, \cdots, h_{R_LB}]^T$, along with h_{iP}, are regarded as CSI. Any receiver end is equally deteriorated by additive white Gaussian noise (AWGN) with zero mean and N_0 variance, which is denoted as n_B here at the BS. The reflective links are a concatenation of three components, the i-th user to the RIS links, the RIS's reflections with phase shifts, and the RIS to the BS links, wherein $i \in \{1, \cdots, N\}$. Although RIS can control appendant amplitudes or phases or both switching in real time, the phase modification is the main focus of this paper. Therefore, under the unit-modulus constraint, we omit the amplitude coefficients, then the reflection coefficient matrix of the RIS is defined as the following diagonal matrix $\boldsymbol{\theta}_i = diag(e^{-j\phi_{i1}}, \cdots, e^{-j\phi_{iL}})$, where $\phi_{in} \in [0, 2\pi]$ denote the phase shifts, wherein $n \in \{1, \cdots, L\}$. So after some manipulations, (4) can also be written as

$$y_{iB} = \sqrt{P_i}\left(\sum_{n=1}^{L} h_{iR_n} h_{R_nB} e^{-j\phi_{in}}\right) x_i + n_B. \tag{5}$$

In the $(1-\beta)T$ transmission time, by substituting (2) into (5), and upon the theory of Shannon theorem, the instantaneous capacity at the BS is given by

$$\begin{aligned} C_{iB} = &(1-\beta)T \\ &\times \log_2\left(1 + \frac{\eta\beta\gamma_b \left|h_{iP}\right|^2}{1-\beta}\Big|\sum_{n=1}^{L} h_{iR_n} h_{R_nB} e^{-j\phi_{in}}\Big|^2\right), \end{aligned} \tag{6}$$

where $\gamma_b = P_b/N_0$ is referred to as the signal-to-noise ratio (SNR) at the PB, T is the unit time slot for transmission, which is specified to $T = 1$ and can be omitted subsequently. Since here the BS is limited to serve one user at a certain moment owing to some facts (e.g. users sharing the same spectrum resource), different users make their communication through time division (TD), and the phase shifts generated by the RIS can be adjusted according to the perfectly known CSI of the exact accessing user. The hardware limit of quantization of phase shifts is beyond the scope of this paper, so we assume an ideal scenario of continuous phase shifts. Hence, $\boldsymbol{\theta}_i$ need to be different in each time slot of user i, when the RIS manages to make phase shifts

$$\phi_{in} = -\arg(h_{iR_n} h_{R_nB}) = -\arg(h_{iR_n}) - \arg(h_{R_nB}), \tag{7}$$

where the concatenation part is denoted as $A_i = \sum_{n=1}^{L} h_{iR_n} h_{R_nB} e^{-j\phi_{in}}$ by us. When the equality (7) is satisfied, A_i is real-valued. Outage probability (OP) is used as our performance metric, which is defined as (for the i-th user)

$$P_{out}^{i} = \Pr(C_{iB} < R), \tag{8}$$

where R is the target rate. If the data speed between the users and the BS is lower than the threshold, the undesired cases of communication suspension occur.

III. Outage performance analysis of the TS-RRS and TS-MCS schemes

A. Closed Form OPs for the Two Schemes

In this section, we present two RIS-aided multi-user scheduling schemes, the TS based round-robin scheduling (TS-RRS) and the TS based maximum capacity scheduling (TS-MCS), and carry out their closed-form OP analysis, respectively. In the TS-RRS scheme, focusing on the fairness of different users and assuming they are all coordinated, the i-th user orderly transmits information with the BS, wherein $i \in \{1, \cdots, N\}$. While in the TS-MCS scheme, the signal is transmitted between the BS and a particular user denoted as the o-th user, which is opportunistically chosen according to the CSI of both reflective links to communicate in the RIS-enhanced communication system, in other words, the o-th user is chosen to improve the combined signal, thus the maximum instantaneous capacity can be achieved, where the name of the scheme comes from. Hence, the user selection criterion we use in the TS-MCS scheme is expressed as

$$o = \underset{\mathrm{i}}{\operatorname{argmax}}\{C_{iB}\}, \tag{9}$$

where $o \in \{1, \cdots, N\}$. In our TS-RRS scheme which is specially designed for TD communication system, we consider that the i-th user takes turns to transmit data with the BS, wherein $i \in \{1, \cdots, N\}$. Let $\alpha_i = 1/N$, which represents the percentage of time period occupied by the i-th user, also referred to as the duty cycle. According to the last section, the OP of the TS-RRS scheme can be given by (10) and be further derived below

$$\begin{aligned} P_{out}^{RRS} &= \sum_{i=1}^{N} \alpha_i \Pr\left(C_{iB}^{RRS} < R\right) \\ &= \sum_{i=1}^{N} \alpha_i \Pr\left(\left|h_{iP}\right|^2 \left|A_i\right|^2 < \frac{(2^{\frac{R}{1-\beta}} - 1)(1-\beta)}{\eta\beta\gamma_b}\right), \end{aligned} \tag{10}$$

Typically, by virtue of the CLT approximation as RIS features its large reflector number, A_i becomes a real Gaussian variable, $A_i \sim \mathcal{N}(L\lambda, L\sigma^2)$. Following the [7], [10] literatures, the statistical means λ and variances σ^2 of A_i are expressed as

$$\lambda = \frac{\sigma_{iR}\sigma_{RB}\pi L_{\frac{1}{2}}(-K_{iR}) L_{\frac{1}{2}}(-K_{RB})}{4\sqrt{(K_{iR}+1)(K_{RB}+1)}}, \tag{11}$$

and

$$\begin{aligned} \sigma^2 = &\sigma_{iR}^2\sigma_{RB}^2 + \frac{\pi\sigma_{iR}^2 L_{\frac{1}{2}}(-K_{iR})^2}{4(K_{iR}+1)} \\ &+ \frac{\pi\sigma_{RB}^2 L_{\frac{1}{2}}(-K_{RB})^2}{4(K_{RB}+1)}, \end{aligned} \tag{12}$$

where $L_{\frac{1}{2}}(.)$ denotes the Laguerre polynomial [11]. To make our calculation of $\left|A_i\right|^2$, T_i is used to replace A_i, which is regarded as a circular symmetric complex Gaussian variable, denoted as $T_i \sim \mathcal{CN}(L\lambda, L\sigma^2/2)$. Therefore the probability density function (PDF) of T_i is

$$\begin{aligned} f_T(t) &= \frac{(k+1)e^{-k}}{\lambda} e^{-\frac{(k+1)t}{\lambda}} I_0\left(2\sqrt{\frac{k(k+1)t}{\lambda}}\right) \\ &= \frac{2}{\lambda} a \sum_{l=0}^{\infty} b(\frac{c}{2\lambda} t)^l e^{-\frac{2}{\lambda} t}, \end{aligned} \tag{13}$$

where $k = \frac{\sqrt{L}\lambda}{\sigma}$, $a = \frac{(k+1)e^{-k}}{2}$, $b = \frac{k^l}{(l!)^2}$, and $c = 2(k+1)$. Here $I_0(.)$ is the zero-th order modified Bessel function of the first kind and can be further expanded as $I_0(x) = \sum_{l=0}^{\infty} \frac{x^{2l}}{2^{2l}(l!)^2}$ [12]. Letting $X_i = |h_{iP}|^2 |A_i|^2$ and following the [13, Eq. (34)] literature, we obtain the PDF of X_i as

$$f_X(x) = a \sum_{l=0}^{\infty} b \left(\frac{k+1}{2}\right)^{\frac{l}{2}} x^{l+1} K_l(\sqrt{c}x). \quad (14)$$

where $K_l(.)$ is the modified Bessel function of the second kind [14, Eq. (8.432.6)]. Utilizing [14, Eq. (6.2.4)], we get the cumulative density function (CDF) of X_i, which can be substituted into (11). Then $\theta = \frac{(2^{\frac{R}{1-\beta}}-1)(1-\beta)}{\eta\beta\gamma_b L\lambda}$ is denoted, and the closed-form OP of the TS-RRS scheme is given by (15) below

$$\begin{aligned} P_{out}^{RRS} &= F_X(\theta) \\ &= a\theta \sum_{l=0}^{\infty} b \left(\frac{k+1}{2}\right)^{\frac{l}{2}} \frac{2^{l-2}}{c^{\frac{l}{2}}} G_{1,3}^{2,1}\left(\begin{matrix} 0 \\ l, 0, -1 \end{matrix} \;\middle|\; \frac{c\theta}{4}\right), \end{aligned} \quad (15)$$

where $G_{m,n}^{p,q}(.)$ is the Meijer G-function [14, Eq. (9.301)].

On the other hand, in the TS-MCS scheme, we conceive the scenario that the index o of the transmitting user is chosen according to the selection criterion mentioned in (9), the particular o-th user is communicating with the BS during whole period of data transmission time. Combining the defination (8) and the selection criterion (9), we get the OP of the TS-MCS scheme below

$$\begin{aligned} P_{out}^{MCS} &= \Pr\left(C_{oB}^{MCS} < R\right) \\ &= \Pr\left(\max_i \left\{\frac{\eta\beta\gamma_b X_i}{1-\beta}\right\} < 2^{\frac{R}{1-\beta}} - 1\right). \end{aligned} \quad (16)$$

Without loss of generality, we consider X_i is i.i.d for different i, which is based on the relatively far distances of each hop reflective links, whereas the users are close to each other. So comparing (16) to (11), and using (15) by contrast, the closed-form OP of the TS-MCS scheme is given by

$$P_{out}^{MCS} = (a\theta)^N \left[\sum_{l=0}^{\infty} b \left(\frac{k+1}{2}\right)^{\frac{l}{2}} \frac{2^{l-2}}{c^{\frac{l}{2}}} G_{1,3}^{2,1}\left(\begin{matrix} 0 \\ l, 0, -1 \end{matrix} \;\middle|\; \frac{c\theta}{4}\right)\right]^N . \quad (17)$$

B. Iterative Algorithm for Optimal Time Splitting Fraction

Based on the closed-form OPs of the TS-RRS and TS-MCS schemes, we attain the optimal time splitting fraction adopting an iterative golden search algorithm, a typical kind of exact one-dimensional search, which is summarized in Algorithm 1. The optimal TS allocation ratio β is numerically determined, presented next.

IV. Numerical Results and Discussions

In this section, we present the numerical OPs of the TS-RRS and TS-MCS schemes in our presented RIS-assisted WPMCN, and highlight the outperformance of TS-MCS scheme. In our

Algorithm 1 Golden Search Algorithm for Obtaining Optimal Time Splitting Factor

1: Initializate $a = 0.1, b = 0.75$, the maximum tolerance $\varepsilon = 10^{-3}$.
2: Calculate $\beta_1 = b - 0.618(b-a)$ and $\beta_2 = a + 0.618(b-a)$.
3: **while** $|\beta_1 - \beta_2| > \varepsilon$ **do**
4: $\quad$ $\beta = \beta_1$, $\beta = \beta_2$, calculate P_{out}^{RRS}, using (15).
5: $\quad$ **if** $P_{out}^{RRS}(\beta_2) \geq P_{out}^{RRS}(\beta_1)$ **then**
6: $\quad\quad$ b = β_2.
7: $\quad\quad$ **else** a = β_1.
8: $\quad$ **end if**
9: **end while**
10: Return the optimal time splitting factor $\beta^* = (a+b)/2$.
11: Repeat process 3 to 10 for P_{out}^{MCS}, using (17).
12: **end**

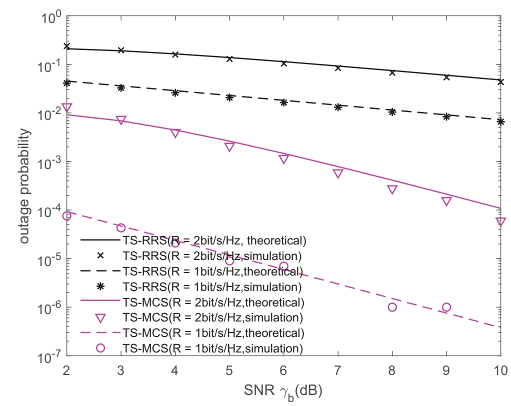

Fig. 2. OPs versus the SNR γ_b at the PB of the TS-RRS and TS-MCS schemes.

numerical simulations, the variances of h_{iP}, h_{iR_n}, and h_{R_nB} are specified to $\sigma_{iP}^2 = 2$, $\sigma_{iR}^2 = 0.5$, and $\sigma_{RB}^2 = 0.5$. We use the SNR $\gamma_b = 10$dB, the number of users $N = 3$, the RIS reflecting elements number $L = 16$, the duty cycle $\alpha_i = 1/N$, the efficiency of energy conversion $\eta = 0.6$, the TS allocation ratio $\beta = 0.6$, and the same Rician factor values of $K_{iR} = K_{RB} = 1$, unless otherwise stated.

Fig. 2 depicts the OP comparison among the TS-RRS and TS-MCS schemes by using (15), (17) for theoretical ones as lines and (10), (16) for simulation ones as discrete markers, which is Monte-Carlo results of the OPs without approximation. As can be witnessed, the theoretical OPs match well with their corresponding Monte-Carlo simulation results, which not only demonstrates our closed-form OP analysis, but also exhibits the accuracy of the CLT approximation. Moreover, with an increasing SNR, the OPs of the proposed TS-MCS scheme reduce more significantly in comparison with the TS-RRS scheme, exhibiting excellent asymptotic outage behaviour.

In Fig. 3, the OPs of both the TS-RRS and TS-MCS schemes decrease when L becomes large. Furthermore, the faster reducing OPs of the TS-MCS scheme indicate the more significant outage advantage of the TS-MCS over TS-RRS

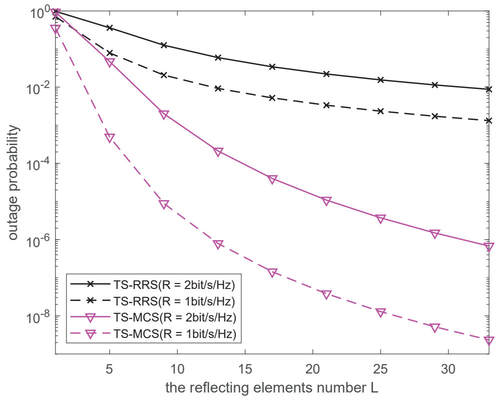

Fig. 3. The impact of the reflector number L on OPs of the TS-RRS and TS-MCS schemes.

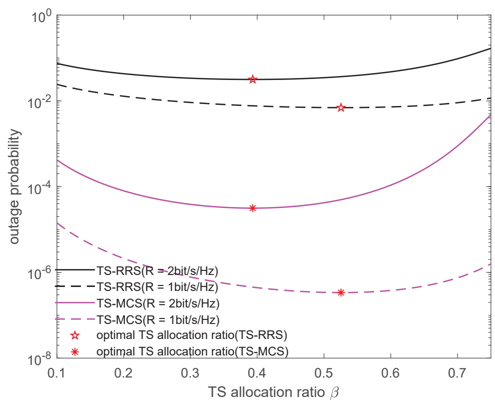

Fig. 4. OPs versus the TS allocation ratio β of the TS-RRS and TS-MCS schemes.

along with an increasing reflector number L. As RISs are also referred to large intelligent surfaces, they are usually integrated with a vast number of reflecting elements, hence an RIS does work well to enhance communication reliability with vast number of reflectors.

It is shown from Fig. 4 that as the TS allocation ratio β grows from 0.1 to 0.75, the OPs of both TS-RRS and TS-MCS schemes first drop to their respective minimums and then start to increase, showing the existence of an optimal TS allocation ratio β to minimize OPs, which can be obtained by the aforementioned iterative algorithm. The exact matches of the numerical optimal TS allocation ratio and the minimum values of the outage probability curves validate the correctness of our adoption of the algorithm. And the obvious appearance of the same lowest points in two different schemes is due to the monotonicity of the power function, as the above theoretical expression in the TS-MCS scheme is N squared as one in the TS-RRS scheme. The curves unveil the outage benefits of EH users, for making proper use of the trade-off concept between the time for EH and for information transmission can gain the WPMCNs lowest OPs. And when the target rate R increases, the optimal TS allocation ratio β appears smaller, owing to the need of the users to spend more time to transmit data.

V. Conclusion

In this paper, we presented an RIS-aided WPMCN framework, and studied the outage performance by deriving closed-form OP expressions of the TS-RRS and TS-MCS schemes. Furthermore, by making use of the theoretical expressions, the OPs of both schemes could be further minimized with an optimized TS allocation ratio, which was also shown in numerical results. Proper time slot partitions between information processing and energy acquiring were found to enhance outage performance of both schemes, especially for the proposed TS-MCS scheme.

Acknowledgment

This work was partially supported by the National Natural Science Foundation of China (Grant Nos. 62071253 and 91738201).

References

[1] W. Saad, M. Bennis, and M. Chen, “A vision of 6G wireless systems: Applications, trends, technologies, and open research problems,” *IEEE Netw.*, vol. 34, no. 3, pp. 134-142, May 2020.

[2] H. Ju and R. Zhang, “User cooperation in wireless powered communication networks,” *Global Communications Conference (GLOBECOM)*, Dec. 2014.

[3] X. Zhou, R. Zhang, and C. K. Ho, “Wireless information and power transfer: Architecture design and rate-energy tradeoff,” *IEEE Trans. Commun.*, vol. 61, no. 11, pp. 4754-4767, Nov. 2013.

[4] Q. Wu and R. Zhang, “Intelligent reflecting surface enhanced wireless network via joint active and passive beamforming,” *IEEE Trans. Wireless Commun.*, vol. 18, no. 11, pp. 5394-5409, Aug. 2019.

[5] S. Gong, X. Lu, and D. Hoang, “Towards smart wireless communications via intelligent reflecting surfaces: A contemporary survey,” *IEEE Commun. Surveys Tuts.*, vol. 22, no. 4, pp. 2283-2314, 4th Quart., 2020.

[6] Q. Wu and R. Zhang, “Joint active and passive beamforming optimization for intelligent reflecting surface assisted SWIPT under QoS constraints,” *IEEE J. Sel. Areas Commun.*, vol. 38, no. 8, pp. 1735-1748, Aug. 2020.

[7] X. Gan, C. Zhong, Y. Zhu, and Z. Zhong, “User selection in reconfigurable intelligent surface assisted communication systems,” *IEEE Commun. Lett.*, vol. 25, no. 4, pp. 1353-1357, Apr. 2021.

[8] L. Yang, Y. Yang, D. B. da Costa, and I. Trigui, “Outage probability and capacity scaling law of multiple RIS-aided networks,” *IEEE Wireless Commun. Lett.*, vol. 10, no. 2, pp. 256-260, Feb. 2021.

[9] Q. Wu and R. Zhang, “Towards smart and reconfigurable environment: Intelligent reflecting surface aided wireless network,” *IEEE Commun. Mag.*, vol. 58, no. 1, pp. 106–112, Jan. 2020.

[10] E. Basar, M. Di Renzo, J. De Rosny, M. Debbah, M. S. Alouini, and R. Zhang, “Wireless communications through reconfigurable intelligent surfaces,” *IEEE Access*, vol. 7, pp. 116753-116773, Aug. 2019.

[11] M. Abramowitz and I. A. Stegun, *Handbook of mathematical functions*, NY: Dover Publication Inc., 1974.

[12] M. K. Simon and M. S. Alouini, *Digital Communication Over Fading Channels*, vol. 95. Hoboken, NJ, USA: Wiley, 2005.

[13] N. O. Donoughue and J. M. F. Moura, “On the product of independent complex Gaussians,” *IEEE Trans. Signal Proc.*, vol. 60, no. 3, pp. 1050-1063, Mar. 2012.

[14] I. S. Gradshteyn and I. M. Ryzhik, *Table of Integrals, Series, and Products*, Academic Press, 2000.