JTE
HCMUTE
ISSN: 2615-9740

JOURNAL OF TECHNICAL EDUCATION SCIENCE
Ho Chi Minh City University of Technology and Education
Website: https://jte.edu.vn
Email: jte@hcmute.edu.vn

Performance Analysis for Hybrid TPSR Energy Harvesting Enabled in Multi-Source Half-Duplex Relaying Network over Rayleigh Fading Channel

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ARTICLE INFO

Received:	11/10/2023
Revised:	11/11/2023
Accepted:	28/11/2023
Published:	28/04/2024

KEYWORDS

Amplify-and-forward;

Energy Harvesting;

Outage Probability;

Relaying network;

Half-duplex.

ABSTRACT

This paper investigates the system performance of hybrid time-power switching based relaying (TPSR) energy harvesting enabled in the multi-source half-duplex relaying network over the Rayleigh fading channel. The outage probability (OP) of the proposed system model with implementing maximal ratio combining (MRC) and selection combination (SC) technique at the receiver is presented and analyzed. The impact of main system parameters, such as transmit signal to noise ratio (SNR), time fraction factor, power fraction factor, and number of sources, on the system performance is analyzed. The results indicate that the performance of the system in the case of MRC is more improved than in the SC case. It shows the benefit of MRC for optimizing SNR at the receiver. Furthermore, we recognize that there exists an optimal value of time fraction factors where the system performance obtains the best performance. Finally, the correctness of the analytical formulation is verified by Monte Carlo simulation.

Doi: https://doi.org/10.54644/jte.2024.1480

1. Introduction

Energy harvesting (EH) is emerging as a potential technology for limited energy networks and wireless devices. Harvesting energy from green sources in the surrounding environment and transforming it into electrical energy for communication networks is a major area of research [1], [2]. Green energy sources in the wireless environment consist of solar, wind, thermal, mechanical vibrations, radio frequency (RF) signals with information transmission or harvesting energy and can be considered as prospective energy sources for sensor nodes [3], [4], [5]. In fifth generation (5G) and beyond networks, EH contributes to reducing power consumption [6]. The concept of wireless power transfer (WPT) has been proposed in [7], and simultaneous wireless information and power transfer (SWIPT) has been suggested as a potential technique that contributed significantly to the development of RF energy harvesting [8]. There are two types of receivers in the cooperative communication network that are time-switching (TS) and power splitting (PS) techniques [9]. In the TS protocol, the EH node changes in time between EH and information processing (IP), while in the PS method, the EH node divides the received power for IP and EH.

Furthermore, the cooperative communication network with the relay node can help the source transfer the information to the destination, which is the hot trend in the communication network [10]-[15]. The authors in [10] considered the performance of multi-hop cognitive wireless sensor networks (WSNs), the secondary source and relays that harvest energy from a power beacon to forward the information. While in [11], the authors derived service time distribution, average waiting time of a packet, queue stability criteria of the secondary user in a cognitive WPCN. Both the AF and DF relaying protocols have been investigated with power splitting-based energy harvesting, and the authors in [12] demonstrated that the advantages of DF. Static or mobile wireless networks are the rich green energy sources for energy harvesting, the authors in [13] proposed that a harvester node collects the energy generated by the coexisting wireless networks and then acts as a transmitter after the duration of harvest. EH in a non-orthogonal multiple access (NOMA) network is considered in [14], where the relay using TS protocol harvests energy from the RF source in the condition of imperfect information on the state of the channel (ICSI). Furthermore, in [15] proposed two successive interference cancellation (SIC) cases in the EH-NOMA network to improve the performance gap between two NOMA destinations. In recent times, cooperative communication systems have been attracted in research to enhance the performance of systems. The authors in [16] considered the performance of energy harvesting based on a power splitting network in different scenarios of fading channels. Nowadays, the rapid development of wireless technology in 5G and beyond requires ensuring quality of service (QoS) and enhancing the performance of the system. The power consumption is a key factor effect on network lifetime, hence EH still is a potential research for solving energy efficiency.

Motivated by these previous discussions, this article investigates the performance of the hybrid TPSR energy harvesting system enabled in the multi-source half-duplex relaying network in the environment condition of the Rayleigh fading channel. The outage probability has been derived with maximal receiver ratio combining (MRC) and selection combining (SC). The main system parameters such as the signal to noise ratio (SNR), time fraction, power fraction and number of sources effect on the system performance are investigated. Finally, the analytical formulation is verified by Monte Carlo simulations. The rest of this paper is organized into the following sections: System model, system performance, numerical results and discussion, and conclusion.

2. System model

We consider a communication scenario where a destination node (D) receives the signal transmitted from a source node (S) through the intermediate relay node (R), as illustrated in Fig. 1. The EH and IP processes of the system model are proposed in Fig. 2. The block time *T* used to transmit the information from *S* to *D* is divided into two parts. In the first duration αT, the transmitted power of S is divided into two parts, the first part ρP_{S_b} is used for EH and the rest of average transmit power $\left(1-\rho\right)P_{S_b}$ is used for information processing from *S* to *R*. The remaining duration $(1-\alpha)T$ is used to transmit information from *R* to *D*. In which, $0<\alpha<1$ denotes the time fraction parameter and $0<\rho<1$ denotes the power splitting ratio.

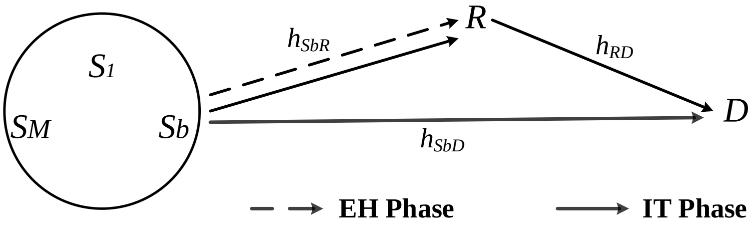

Fig. 1. *System model.*

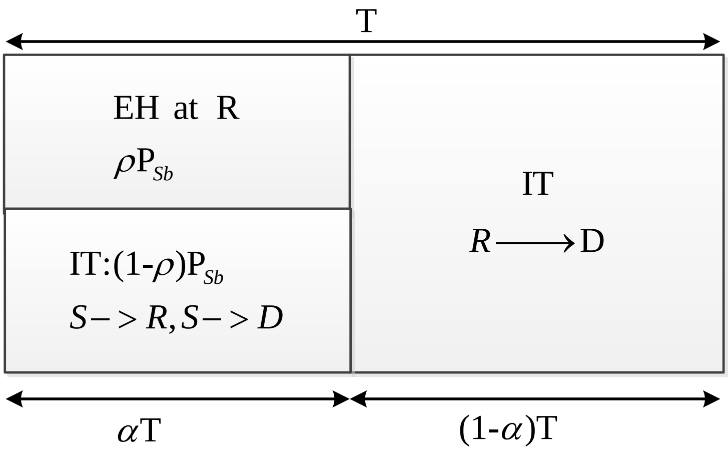

Fig. 2. *The EH and IT phases.*

The relay received the signal during the first transmission stage, which can be expressed as

$$y_r = \sqrt{(1-\rho)} h_{S_bR} x_{S_b} + n_r \tag{1}$$

Where $b \in (1,2,...,M)$; x_{S_b} is the signal transmitted at the source, n_r denotes the additive white Gaussian noise (AWGN) with variance N_0 and $\mathrm{E}\left\{\left|x_{S_b}\right|^2\right\} = P_{S_b}$, $\mathrm{E}\{\bullet\}$: expectation operator, (P_{S_b} : average transmit power at the b^{th} source).

The harvested power at the relay R can be obtained as:

$$P_r = \frac{E_h}{(1-\alpha)T} = \frac{\eta\rho\alpha T P_{S_b} \left|h_{S_bR}\right|^2}{(1-\alpha)T} = \kappa P_{S_b} \left|h_{S_bR}\right|^2 \tag{2}$$

where $\kappa = \frac{\eta\rho\alpha}{1-\alpha}$ and $0 < \eta \le 1$ is the energy conversion efficiency.

The received signal at the destination (D) from the relay and source in the transmission phase can be expressed as, respectively.

$$\begin{aligned} y_D^1 &= h_{S_bD} x_s + n_D^1, \\ y_D^2 &= h_{RD} x_r + n_D^2 \end{aligned} \tag{3}$$

where h_{RD} is the relay to the destination channel gain, $n_D^1 = n_D^2 = n_D$ is AWGN with variance N_0 and $\mathrm{E}\left\{\left|x_r\right|^2\right\} = P_r$

We deploy the amplify-and-forward (AF) technique in the proposed system model. Therefore, the relay transmits the signal amplified from y_r, which is denoted by factor β

$$\beta = \frac{x_r}{y_r} = \sqrt{\frac{P_r}{(1-\rho)P_{S_b}\left|h_{S_bR}\right|^2 + N_0}} \tag{4}$$

From (3) and (4), the signal received at D in the second stage can be represented by

$$\begin{aligned} y_D^2 &= h_{RD}\beta y_R + n_D^2 \\ &= h_{RD}\beta\left[\sqrt{(1-\rho)} h_{S_bR} x_{S_b} + n_R\right] + n_D^2 \\ &= \underbrace{\sqrt{(1-\rho)} h_{S_bR} x_{S_b} h_{RD}\beta}_{signal} + \underbrace{h_{RD}\beta n_R + n_D^2}_{noise} \end{aligned} \tag{5}$$

Hence, SNR at D in this stage can be presented by

$$\begin{aligned} \gamma_D^2 &= \frac{\mathrm{E}\left\{\left|signal\right|^2\right\}}{\mathrm{E}\left\{\left|noise\right|^2\right\}} = \frac{(1-\rho)P_{S_b}\left|h_{S_bR}\right|^2\left|h_{RD}\right|^2\beta^2}{\left|h_{RD}\right|^2\beta^2 N_0 + N_0} \\ &= \frac{(1-\rho)P_{S_b}\left|h_{S_bR}\right|^2\left|h_{RD}\right|^2}{\left|h_{RD}\right|^2 N_0 + \frac{N_0}{\beta^2}} \end{aligned} \tag{6}$$

After performing some algebraic calculations and using the fact that $N_0 << P_r$

$$\gamma_D^2 = \frac{(1-\rho)P_{S_b}P_r\left|h_{S_bR}\right|^2\left|h_{RD}\right|^2}{\left|h_{RD}\right|^2 P_r N_0 + (1-\rho)P_{S_b}\left|h_{S_bR}\right|^2 N_0} \tag{7}$$

And then by combining with (2); finally, we have:

$$\gamma_D^2 = \frac{\kappa(1-\rho)\Psi\left|h_{S_bR}\right|^2\left|h_{RD}\right|^2}{\kappa\left|h_{RD}\right|^2 + (1-\rho)} \tag{8}$$

where $\Psi = P_{S_b} / N_0$.

In this phase, D also is received the direct signal from the random source. Therefore, the SNR can be computed as

$$\gamma_D^1 = \Psi\left|h_{S_jD}\right|^2 \tag{8}$$

where $j \in (1,...,M)$

Remark

The best source would be selected to maximize the received SNR γ_D^2 at the destination to optimize the transmission performance.

$$b^* = \arg\max_{1\le b\le M}\left[\gamma_D^2\right] \tag{9}$$

We deploy the best source selection by proposing the optimal source selection protocol, which is denoted as follows,

$$\omega_1 = \max_{b=1,2,...,M}\left(\left|h_{S_bR}\right|^2\right) \tag{10}$$

Here, the Cumulative Distribution Function (CDF) of ω_1 is as follows

$$F_{\omega_1}(x) = \sum_{n=0}^{M}(-1)^n C_M^n \times e^{-\lambda_1 nx} = 1 + \sum_{n=1}^{M}(-1)^n C_M^n \times e^{-\lambda_1 nx} \tag{11}$$

Where $C_M^n = \dfrac{M!}{n!(M-n)!}$ and λ_1 is the mean of the random variable (RV) ω_1.

Then, we obtain the Probability Density Function (PDF) of ω_1:

$$f_{\omega_1}(x) = \lambda_1\sum_{n=0}^{M-1}\left(-1\right)^n C_{M-1}^n M \times e^{-\lambda_1(n+1)x} \tag{12}$$

3. System Performance

Outage Probability (OP)

The OP of the system can be defined as

$$OP = \Pr\left(\gamma_{AF}^i < \gamma_{th}\right) \tag{13}$$

where γ_{th} is the predefined threshold of the system and $i \in (MRC, SC)$.

A. Using MRC technique at the receiver

In this technique, the overall receiver SNR at D can be given as following after using results from (7) and (8).

$$\gamma_{AF}^{MRC} = \gamma_D^1 + \gamma_D^2 = \frac{\kappa(1-\rho)\Psi\omega_1\omega_2}{\kappa\omega_2 + (1-\rho)} + \Psi\omega_3 \tag{14}$$

Where $\omega_2 = \left|h_{RD}\right|^2, \omega_3 = \left|h_{S_jD}\right|^2$.

Substituting (14) into (13), the OP, in this case, can be found as

$$
\begin{aligned}
OP_{MRC} &= \Pr\left(\frac{\kappa(1-\rho)\Psi\omega_1\omega_2}{\kappa\omega_2+(1-\rho)}+\Psi\omega_3<\gamma_{th}\right)\\
&= \Pr\left(X+Y<\gamma_{th}\right)=\int_0^{\gamma_{th}} F_X(\gamma_{th}-y)\times f_Y(y)dy
\end{aligned}
\tag{15}
$$

where $X=\frac{\kappa(1-\rho)\Psi\omega_1\omega_2}{\kappa\omega_2+(1-\rho)}, Y=\Psi\omega_3$.

Next, at first we will find the CDF of X and PDF of Y as followings

$$
\begin{aligned}
F_X(x) &= \Pr\left(\frac{\kappa(1-\rho)\Psi\omega_1\omega_2}{\kappa\omega_2+(1-\rho)}<x\right)=\Pr\left(\omega_1<\frac{x\left(\kappa\omega_2+(1-\rho)\right)}{\kappa(1-\rho)\Psi\omega_2}\right)\\
&= \Pr\left(\omega_1<\frac{x}{(1-\rho)\Psi}+\frac{x}{\kappa\Psi\omega_2}\right)\\
&= \int_0^{\infty} F_{\omega_1}\left(\frac{x}{(1-\rho)\Psi}+\frac{x}{\kappa\Psi\omega}\right)\times f_{\omega_2}(\omega)d\omega
\end{aligned}
\tag{16}
$$

By using (11), equation (16) can be rewritten by

$$
F_X(x)=1+\sum_{n=1}^{M}(-1)^n C_M^n\times\lambda_2\exp\left(-\frac{\lambda_1 nx}{(1-\rho)\Psi}\right)\int_0^{\infty}\exp\left(\frac{-\lambda_1 nx}{\kappa\Psi\omega}-\lambda_2\omega\right)d\omega
\tag{17}
$$

where λ_2 is the mean of RV ω_2.

Applying eq[3.324, 17], $F_X(x)$ can be derived as

$$
F_X(x)=1+2\sum_{n=1}^{M}(-1)^n C_M^n\times\sqrt{\frac{\lambda_1\lambda_2 nx}{\kappa\Psi}}\times\exp\left(-\frac{\lambda_1 nx}{(1-\rho)\Psi}\right)\times K_1\left(2\sqrt{\frac{\lambda_1\lambda_2 nx}{\kappa\Psi}}\right)
\tag{18}
$$

Moreover, the CDF of Y can be computed by

$$
\begin{aligned}
F_Y(y) &= \Pr(Y<y)=\Pr\left(\Psi\omega_3<y\right)=\Pr\left(\omega_3<\frac{y}{\Psi}\right)\\
&= 1-\exp\left(\frac{-\lambda_3 y}{\Psi}\right)
\end{aligned}
\tag{19}
$$

where λ_3 is the mean of RV ω_3.

Hence, the PDF of Y can be obtained as

$$
f_Y(y)=\frac{\partial F_Y(y)}{\partial y}=\frac{\lambda_3}{\Psi}\exp\left(-\frac{\lambda_3 y}{\Psi}\right)
\tag{20}
$$

Finally, substituting (18) and (20) into (15), the OP_{MRC} can be claimed by

$$
OP_{MRC}=\frac{\lambda_3}{\Psi}\int_0^{\gamma_{th}}\left\{\begin{array}{l}1+2\sum_{n=1}^{M}(-1)^n C_M^n\times\sqrt{\frac{\lambda_1\lambda_2 n(\gamma_{th}-y)}{\kappa\Psi}}\\ \times\exp\left(-\frac{\lambda_1 n(\gamma_{th}-y)}{(1-\rho)\Psi}\right)\times K_1\left(2\sqrt{\frac{\lambda_1\lambda_2 n(\gamma_{th}-y)}{\kappa\Psi}}\right)\end{array}\right\}\times\exp\left(\frac{-\lambda_3 y}{\Psi}\right)dy
\tag{21}
$$

B. Using SC technique at the receiver

In SC technique, the end-to-end SNR at D can be expressed as

$$\begin{aligned}\gamma_{AF}^{SC} &= \max\left(\gamma_D^1, \gamma_D^2\right) = \max\left(\frac{\kappa(1-\rho)\Psi\omega_1\omega_2}{\kappa\omega_2 + (1-\rho)}, \Psi\omega_3\right) \\ &= \max\left(X, Y\right)\end{aligned} \tag{22}$$

The OP, in this case, can be calculated by

$$\begin{aligned}OP_{SC} &= \Pr\left(\gamma_{AF}^{SC} < \gamma_{th}\right) = \Pr\left(\max(X,Y) < \gamma_{th}\right) \\ &= \Pr\left(X < \gamma_{th}\right)\Pr\left(Y < \gamma_{th}\right) \\ &= F_X\left(\gamma_{th}\right) \times F_Y\left(\gamma_{th}\right)\end{aligned} \tag{23}$$

Using the results from (18) and (19), the OP_{SC} can be obtained as

$$\begin{aligned}OP_{SC} = &\left\{1 + 2\sum_{n=1}^{M}(-1)^n C_M^n \times \sqrt{\frac{\lambda_1\lambda_2 n\gamma_{th}}{\kappa\Psi}} \times \exp\left(-\frac{\lambda_1 n\gamma_{th}}{(1-\rho)\Psi}\right) \times K_1\left(2\sqrt{\frac{\lambda_1\lambda_2 n\gamma_{th}}{\kappa\Psi}}\right)\right\} \\ &\times\left(1 - \exp\left(-\frac{\lambda_3\gamma_{th}}{\Psi}\right)\right)\end{aligned} \tag{24}$$

4. Numerical Results and Discussion

In this section, we perform Monte Carlo simulations to validate the derived analytical results and analyze the performance of the system with the detailed simulation parameters shown in the figures. Fig. 3 is the results of the OP versus ψ, overall observation shows that performance of the system significantly increases according to ψ rises from -5 to 15 dB. The system performance improves in the case of MRC compared to SC despite varying the power and time fraction parameters. These results demonstrate that the outstanding advantage of MRC is that the total SNR achieved a more optimal value. Furthermore, OP will decrease when increasing the number of sources M shown in Fig. 4. In fact, the increase of number of sources will lead to the the ability of the R and D to receive successfully information from the multi-sources will be higher than using one source. It will make to improve the received SNR at D. Hence, the result can be shown that the benefit of the number of sources will enhance the system performance. The accuracy of the equations obtained is also demonstrated by the matching between the simulation results and the analytical values.

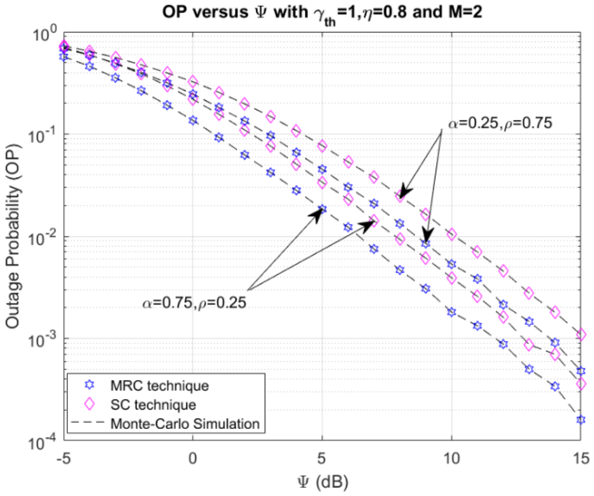

Fig. 3. *OP versus ψ.*

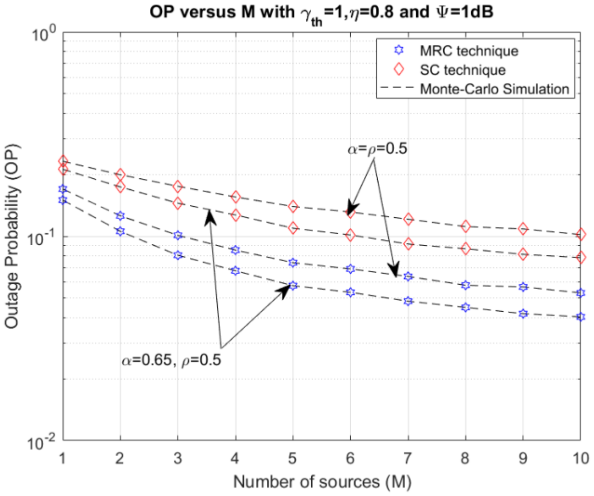

Fig. 4. *OP versus M.*

In addition, the effect of the time fraction factor α and power fraction factor ρ on the system performance is illustrated in Figs.5 and 6, respectively. It is clear that α has a significant effect on the system performance, which is shown in Fig. 5. There exists an optimal range of time fraction for best performance of the system that is around between 0.2 to 0.4, when exceeding the optimal range, the OP of the system decreases drastically. This emphasizes the importance of choosing time fraction parameters to achieve optimal performance of the system. The MRC case has better performance than the SC case. In Fig. 6, the OP slightly improves when increasing the power fraction parameter, and the MRC case also has better performance than the SC case, since it directly maximizes the SNR, while selection combining does not. Totally, from the results in Figs.5 and 6, the system performance when using MRC or SC depends on the reasonable selection of time fraction and power splitting ratio, which contributes to designing the TPSR system. Finally, the analytical results were confirmed by comparing the simulation results, which showed a good agreement.

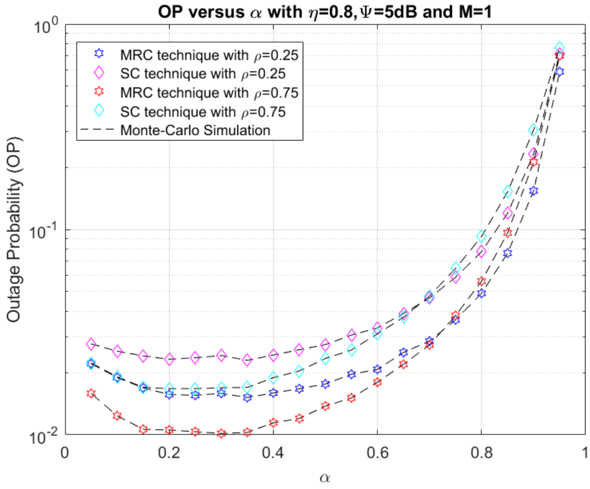

Fig. 5. *OP versus α.*

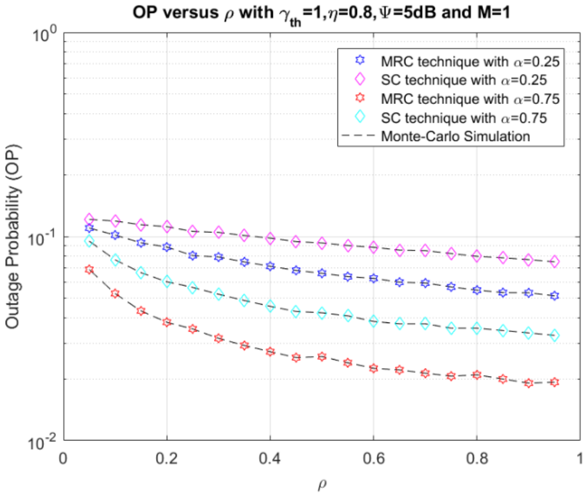

Fig. 6. *OP versus ρ.*

5. Conclusion

In this paper, we propose and investigate the system performance of hybrid TPSR energy harvesting enabled in the multi-source half-duplex relaying network over the Rayleigh fading channel. The outage probability of the proposed system with maximal receiver ratio combining (MRC) and selection combining (SC) is presented and analyzed. From the numerical results, the performance of the system is more improved in the case of MRC compared to SC case and impact varying the time and power fraction factors, specifically there exit the optimal range of time fraction parameter. Finally, the correctness of the analytical formulation is verified by Monte Carlo simulation.

Conflict of Interest

The authors declare no conflict of interest.

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