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Solar Energy Harvesting Using a Timer-Based Relay Selection

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Abstract: In this paper, the throughput and delay of cooperative communications are derived when solar energy is used and relay node is selected using a timer. The source and relays harvest energy from sun using a photo voltaic system. The harvested power is used by the source to transmit data to the relays. Then, a selected relay amplifies the signal to the destination. Opportunistic, partial and reactive relay selection are used. The relay transmits when its timer elapses. The timer is set to a value proportional to the inverse of its Signal to Noise Ratio (SNR). Therefore, the relay with largest SNR will transmit first and its signal will be detected by the other relays that will remain idle to avoid collisions. Harvesting duration is optimized to maximize the throughput. Packet's waiting time and total delay are also computed. We also derive the statistics of SNR when solar energy is used. The harvested power from sun is proportional to the sum of a deterministic radiation intensity and a random attenuation due to weather effects and clouds occlusion. The fixed radiation intensity depends on season, month and time t in hour. The throughput of cooperative communications with energy harvesting from sun was not yet studied.

Keywords: Solar energy harvesting; timer based relay selection; relaying techniques; throughput and delay analysis

1 Introduction

In solar energy harvesting, the harvested power is proportional to the radiation intensity I(t) [1–3]. The radiation intensity is the sum of a deterministic radiation intensity I1(t) and a random radiation intensity I2(t) [4–7]. I1(t) is a deterministic radiation intensity that depends on time t in hour, month and season. I1(t) is maximum at $t = 12$ h and zero at $t = 6$ and $t = 18$ [8–10]. I2(t) is a random attenuation due to weather effects as well as clouds occlusion [11–15]. I2(t) has a zero mean Gaussian distribution with variance a^2 [1]. Therefore, the harvested power has a Gaussian density. In this article, we study cooperative communications with energy harvesting from sun. The source and relays harvest energy using a photo voltaic system. The source use the harvested power to transmit data to relays. Relay nodes harvest energy from sun and set a timer to a value proportional to the inverse of its Signal to Noise Ratio (SNR). The timer of relay with largest SNR will expire first. This relay amplifies the source signal and its signal will be detected by the other relays that will remain idle to avoid collisions. We use Opportunistic Amplify and Forward (OAF), Partial and Reactive Relay Selection (PRS and RRS). The main contributions of the paper are

A simple timer based relay selection is used. The throughput, the collision and the delay of timer based relay selection will be derived. The throughput is maximized by optimizing harvesting duration.

The motivation of this work is to evaluate the throughput and delays with solar energy harvesting. Another motivation is to evaluate the performance of the suggested timer based relay selection. The main contribution of the paper is to derive the statistics of SNR with solar energy harvesting. The throughput, waiting time and total delay are evaluated with solar energy harvesting. A simple relay selection process using a timer is suggested. No signalization is required and the selection process is very simple since each relays uses a timer initialized to a value proportional to the inverse of its SNR. The relay with largest SNR transmits and the other relays remain idle when they detect its signal to avoid collisions. The throughput and delay analysis with energy harvesting from sun were not yet derived.

Section 2 studies the statistics of the harvested power from sun. The collision probability of timer based relay selection is evaluated in Section 3. Section 4 evaluates the throughput, packets' waiting time and total delay. Section 5 comments on the obtained results. Section 6 concludes the paper.

2 Solar Energy Harvesting

Fig. 1 shows the system model where the source S and relays Ri harvest energy from sun using a Photo Voltaic (PV) system. Then, S sends data to relays Ri. A selected relay amplifies the signal to the destination D. The harvested solar power using a PV system at noon is approximately 1000 W/m^2. The harvested power P at the source S and relays Ri using a PV system is proportional to the radiation intensity.

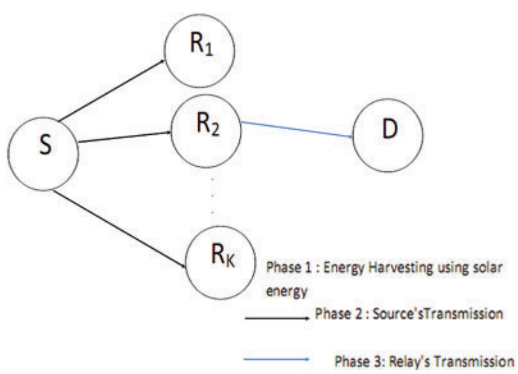

Figure 1: Network model

$$P = \eta I(t), \tag{1}$$

where η is the efficiency of power conversion and I(t) is the radiation intensity. The radiation intensity is the sum of a deterministic radiation intensity I1(t) and a random attenuation I2(t) [16–18]

$$I(t) = I1(t) + I2(t) \tag{2}$$

where I1(t) is a deterministic radiation intensity that depends on time $6 \leq t \leq 18$ in hour, month and season. I1(t) is modeled as [1]

$$I1(t) = Imax\left(-3 + t\frac{2}{3} - \frac{t^2}{36}\right) \tag{3}$$

where Imax is the maximum of radiation intensity.

The harvested solar power using a PV system at noon t = 12 is approximately 1000 W/m^2. For a PV system of 2 m^2, the maximum solar radiation intensity is Imax = 2000 W. I2(t) is a random attenuation due to weather effects as well as clouds occlusion. I2(t) has a zero mean Gaussian distribution with variance a^2 [1]. Therefore, the Probability Density Function (PDF) of I(t) is expressed as [1]

$$f_I(x) = \frac{1}{\sqrt{2\pi a^2}}\exp\left(\frac{-(x - I1(t))^2}{2a^2}\right) \tag{4}$$

where x > 0 is the variable of PDF function and a^2 is the variance of random attenuation I2(t).

Energy harvesting from the PV system is performed continuously. The harvested energy during αT seconds is used to transmit data by S and a selected relay during (1−α)T/2 s where 0 < α < 1 and T is frame length. The harvested energy by the source and relays during αT seconds is expressed as [1]

$$E = \alpha TP \tag{5}$$

The symbol energy Es is the ratio of the harvested energy E given in (5) and the number of transmitted symbols $(1 - \alpha)\, T/Ts$ [1]

$$E_s = \frac{2T_sE}{(1-\alpha)T} = \frac{2\alpha\eta T_sI(t)}{1-\alpha} \tag{6}$$

where Ts is the symbol duration.

Since I(t) has a Gaussian distribution, Es follows also a Gaussian distribution with PDF

$$f_{Es}(x) = \frac{1}{\sqrt{2\pi\sigma^2}}\exp\left(\frac{-(x - m(t))^2}{2\sigma^2}\right) \tag{7}$$

where m(t) and σ^2 are the mean and the variance of Es written as

$$m(t) = \frac{\eta 2\alpha T_sI1(t)}{1-\alpha} \tag{8}$$

$$\beta^2 = \left[\frac{a\eta 2\alpha T_sI1(t)}{1-\alpha}\right]^2 \tag{9}$$

The SNR at relay Rk is written as

$$\gamma_{SRk} = \frac{Es\,|h_{SRk}|^2}{N0} \tag{10}$$

where hXY is channel gain of the X-Y link and N0 is noise variance.

Let $E(|hSRk|^2) = \lambda k = PL\, d0^{PLE}/dSRk^{PLE}$ where PL is the path loss at distance d0, dXY is the distance from X to Y. Let $Zk = |hSRk|^2/N0$. For Rayleigh channels, Xk follows an exponential distribution with Cumulative Distribution Function (CDF) equal to

$$F_{Zk}(x) = 1 - \exp\left(-x\frac{N0}{k}\right), \tag{11}$$

Therefore, the SNR is the product a Gaussian random variable (r.v.) Es and an exponential r.v. Xk. The Cumulative Distribution Function (CDF) of the SNR can be computed as follows [19]:

$$F_{\gamma_{SRk}}(x) = \int_0^{+\infty} f_{Es}(y) F_{Zk}\left(\frac{x}{y}\right) dy \tag{12}$$

The CDF of SNR of Rk-D link is written similarly.

3 Collision Probability

The relay selection process uses a timer. Each relay sets a timer proportional to the inverse of its SNR. Therefore, the timer of the relay with best SNR expires the first and amplifies the signal to the destination. When the relay transmits the other relays detects its signals and remain idle to avoid collisions. Let Xk be the timer of relay Rk

$$X_k = \frac{\beta}{\gamma_{SRk}} \tag{13}$$

when Partial Relay Selection (PRS) is employed. $\beta > 0$ is a constant used to set the timer.

$$X_k = \frac{\beta}{\gamma_{RkD}} \tag{14}$$

when Reactive Relay Selection (RRS) is employed.

$$X_k = \frac{\beta}{\gamma_{SRkD}} \tag{15}$$

when opportunistic relay selection is employed and γSRkD = min(γSRk, γRkD).

Let X(1) be the timer of best relay and X(k) be the timer of k-th best relay: X(1) < X(2) < … < X(K).

There is a collision if the gap between the timer of second best relay X(2) and that of the best relay X(1) is lower than the propagation between d between relay nodes:

$$X(2) < X(1) + d \tag{16}$$

The joint PDF of X(1) and X(2) is expressed as [20]

$$f_{X(1),X(2)}(x1, x2) = \sum_{i=1}^{K} \sum_{j \neq i,\, j=1}^{K} f_{Xj}(x2) f_{Xi}(x1) \prod_{k=1, k\neq i, k\neq j}^{K} \left[1 - F_{Xk}(x2)\right], \tag{17}$$

The collision probability is equal to

$$cp = \int_{x2=d}^{+\infty} \int_{x1=x2-d}^{+\infty} f_{X(1),X(2)}(x1, x2)\, dx1\, dx2 \tag{18}$$

fXk(x) is computed by a simple derivative of FXk(x).

4 Throughput and Delay Analysis

The throughput at D using OAF and a timer based relay selection is computed as:

$$Thr^{OAF} = 0.5(1 - a)[1 - cp] \log 2(M)[1 - PEP^{OAF}], \tag{19}$$

where M is the constellation size, cp is the collision probability and PEP^{OAF} is the Packet Error Probability (PEP) of OAF.

The throughput of PRS with timer based relay selection is computed as:

$$\mathrm{Thr}^{\mathrm{PRS}} = 0.5(1-\mathrm{a})[1-\mathrm{cp}]\log 2(\mathrm{M})[1-\mathrm{PEP}^{\mathrm{PRS}}], \tag{20}$$

$\mathrm{PEP}^{\mathrm{PRS}}$ is the PEP of PRS.

The throughput of RRS with timer based relay selection is computed as:

$$\mathrm{Thr}^{\mathrm{RRS}} = 0.5(1-\mathrm{a})[1-\mathrm{cp}]\log 2(\mathrm{M})[1-\mathrm{PEP}^{\mathrm{RRS}}], \tag{21}$$

where $\mathrm{PEP}^{\mathrm{RRS}}$ is the PEP of RRS relaying.

The PEP of different relaying techniques are computed as [19]

$$\mathrm{PEP}^{\mathrm{OAF}} < \mathrm{F}\gamma^{\mathrm{OAF}}(\mathrm{TH}) \tag{22}$$

$$\mathrm{PEP}^{\mathrm{PRS}} < \mathrm{F}\gamma^{\mathrm{PRS}}(\mathrm{TH}) \tag{23}$$

$$\mathrm{PEP}^{\mathrm{OAF}} < \mathrm{F}\gamma^{\mathrm{OAF}}(\mathrm{TH}) \tag{24}$$

$$TH = \int_0^{+\infty} 1 - [1 - SEP(w)]^L \, dw, \tag{25}$$

L is packet length and [21]

$$SEP(w) = 2\left(1 - \frac{1}{\sqrt{M}}\right) erfc\left(\sqrt{\frac{3w}{M-1}}\right), \tag{26}$$

The average waiting time W of packets is given by the Pollaczek Khinchin formula [22]:

$$W = \frac{\lambda E\left(TR^2\right) T^2}{2\left(1 - \lambda E\left(TR\right)\right)} + 0.5T, \tag{27}$$

λ is packet arrival rate, TR is the number of transmission attempts [21]

$$E(TR) = \frac{1}{1 - PEP}, \tag{28}$$

$$E(TR^2) = \frac{3PEP^2}{(1-PEP)^2} + \frac{3}{1-PEP} - 2, \tag{29}$$

The total delay D is equal to the average waiting time plus the service time, E(TR)T, expressed as

$$D = W + E(TR)T, \tag{30}$$

5 Theoretical and Simulation Results

Figs. 2–4 depict the throughput of timer based relay selection using OAF, PRS and RRS for cp = 0.2, 0.1, 0.05. The curves were plotted *vs.* the average Signal to Noise Ratio (SNR) per it Eb/N0. Eb is the average transmitted energy per bit and N0 is noise variance. The distance between source and relays is 5 and the distance between relays and destination is 4. The path loss exponent was set to three. The size of the PV system was 0.5 m^2 . The used parameters are $\eta = 0.5$, $\alpha = 0.5$, the variance of radiation intensity is $a^2 = 1$ and t = 12. The number of relays is K = 2. We observe that the performance improves as cp decreases and becomes close to best relay selection due to less collisions. In fact as cp decreases as there are less collisions and a larger throughput is achieved. Fig. 5 shows that OAF offers the best performance as it uses the SNR of two hops. PRS is better than RRS since the relays are closer to the destination. In fact, PRS selects the best relay of first hop and offers good performance when relays are close to the destination. RRS selected the best relay of second hop and offers good performance when relays are close to the source. Fig. 6 shows that the throughput of OAF is better at t = 12 since the solar energy is larger than t = 8. Fig. 7 shows that we can increase the throughput of OAF by optimizing the value of harvesting duration α. When α is very small, the harvested power is small and the performance is bad. When α is very large, the harvested power is large but the remaining time for communication is small leading to a small throughput. Fig. 8 shows that the throughput can be easily maximized as it is a concave function with respect to α and there is a single maximum. Fig. 9 shows the total delay for T = 1 ms and arrival rate $\lambda = 0.001$. We observe that the timer based relay selection offers similar delays to best relay selection for cp = 0.05 since there are only few collisions.

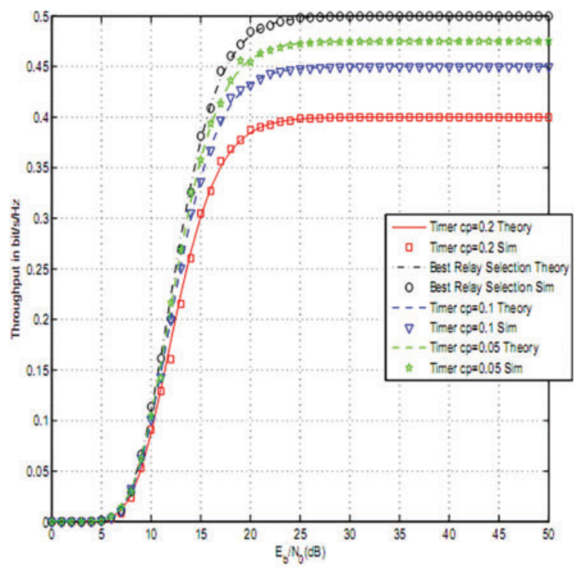

Figure 2: OAF using a timer based relay selection

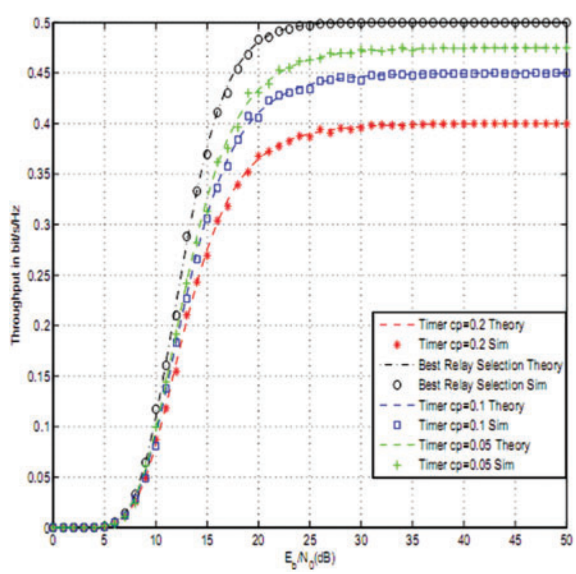

Figure 3: PRS using a timer-based relay selection

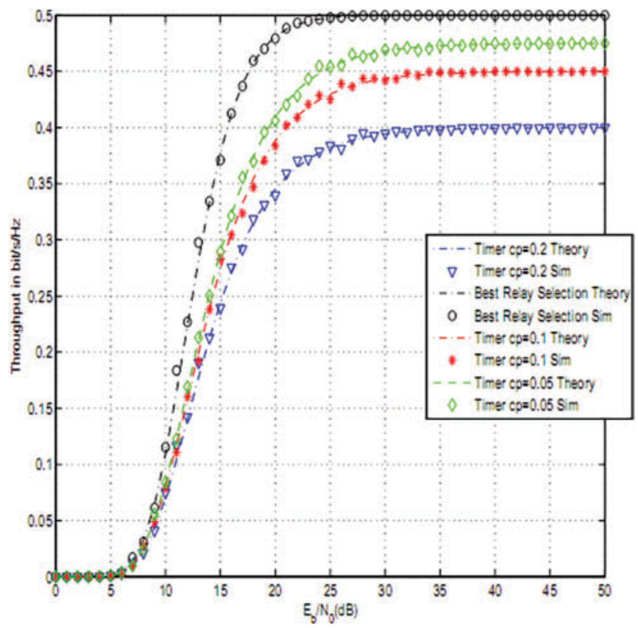

Figure 4: RRS using a timer based relay selection

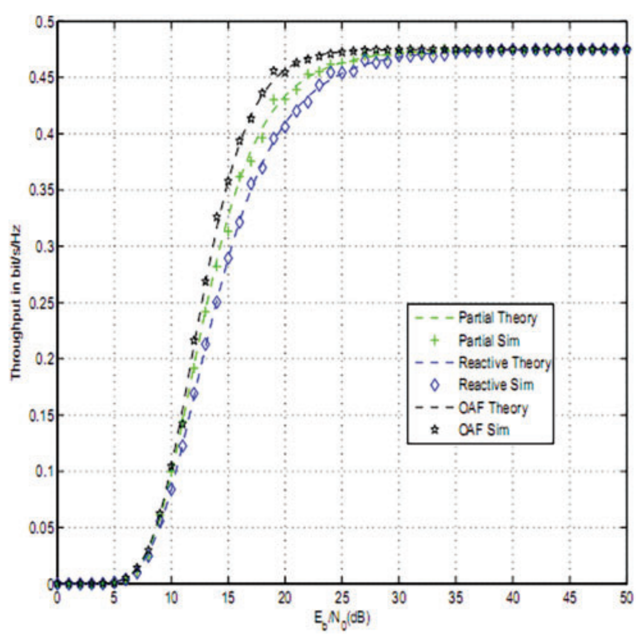

Figure 5: OAF, PRS and RRS for cp = 0.05

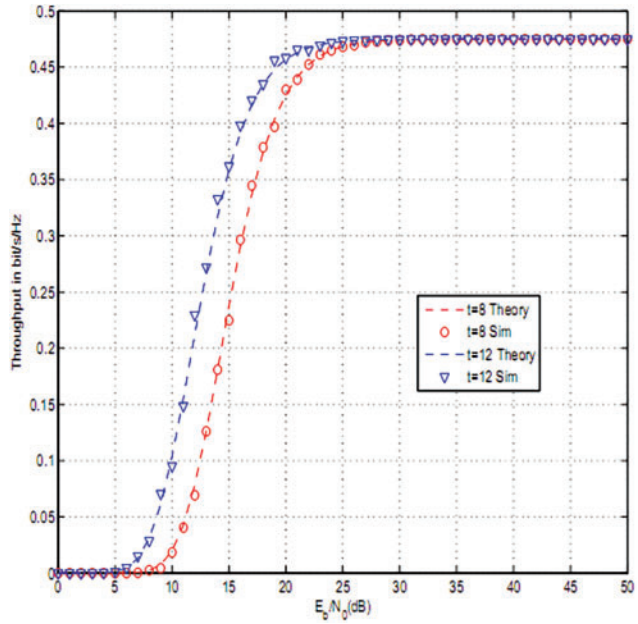

Figure 6: Throughput of OAF for cp = 0.05, K = 2 and t = 8, 12

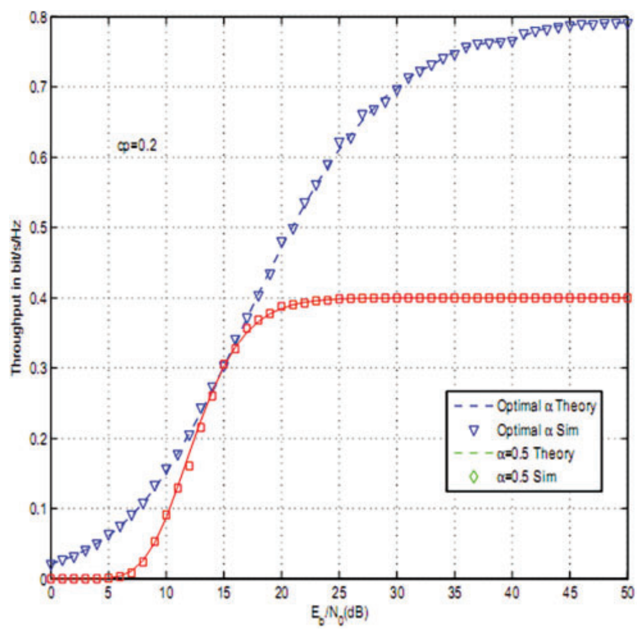

Figure 7: Throughput optimization of OAF for cp = 0.2

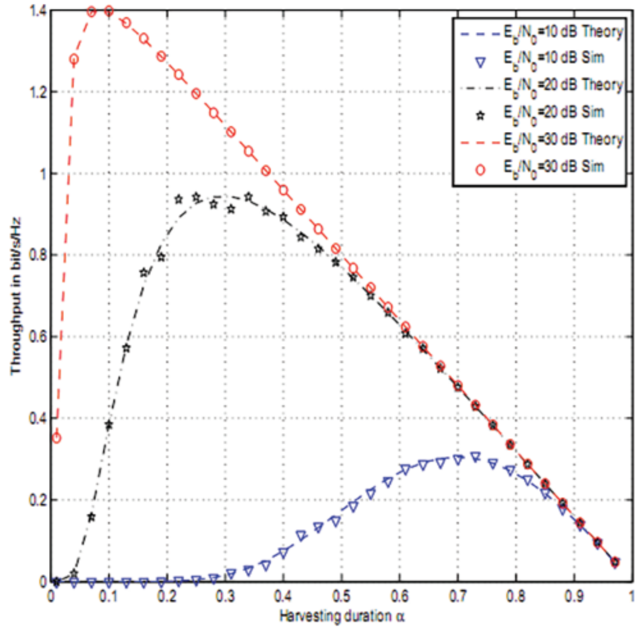

Figure 8: Throughput of OAF *vs.* α for cp = 0.2

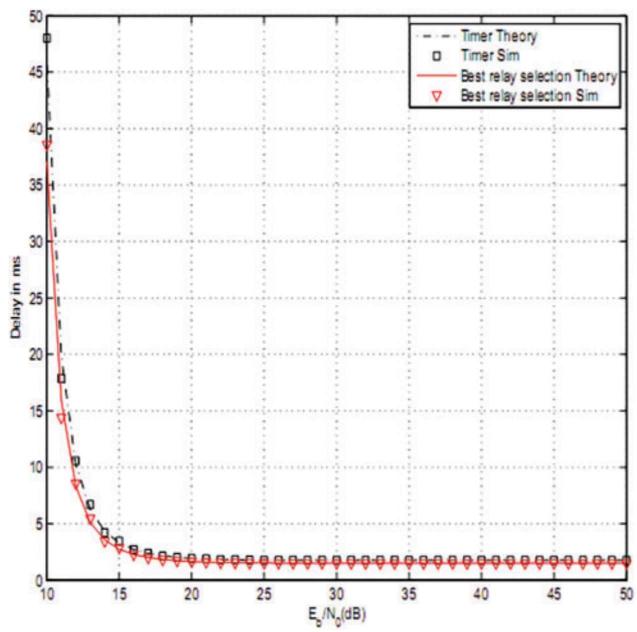

Figure 9: Total delay of OAF for cp = 0.05

6 Conclusions

In this article, the throughput, packets' waiting time and total delay of cooperative communication with solar energy harvesting are derived. The relay selection process uses a timer. Each relay sets a timer proportional to the inverse of its SNR. Therefore, the timer of the relay with best SNR expires the first and amplifies the signal to the destination. When the relay transmits the other relays detects its signals and remain idle to avoid collisions. The throughput was also maximized by optimizing harvesting duration.

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Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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