Research on the Maximization of Total Information Rate Based on Energy Allocation in Multi-user SWIPT Relaying System

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Abstract. With the rapid development and wide application of the wireless communication network, the communication network based on the simultaneous wireless information and power transfer (SWIPT) technology has attracted more and more extensive research. This technology solves the problem of frequent charging or replacement of the device battery very well, has greatly extended the working hours of the device, and can be adapted to some special communication environments such as high temperature and high pressure. This paper studies the effect of the energy allocation in multi-user SWIPT relaying system on the information rate. Thereinto, the relay uses the energy harvested in the energy harvesting mode to amplify and forward the information of the users. The total information rate maximization model is proposed and the corresponding energy allocation scheme is derived. The simulation results show that the proposed energy allocation scheme can maximize the total information rate of all users.

Keywords: Simultaneous wireless information and power transfer (SWIPT) · Multi-user relaying system · Amplify-and-forward · Information rate

1 Introduction

With the rapid development of human civilization, people gradually realize the importance of green energy. The sun and the wind can produce green energy. In addition, the radio frequency (RF) signals can not only transmit information, but also carry energy. The energy harvesting (EH) technology based on RF signals plays an important role in the field of communication. In recent years, there has been an upsurge of research interests in RF-EH technique [1]. As a promising wireless technology, RF-EH technique is getting more and more research. The EH networks based on RF have found their applications quickly in various forms, such as wireless sensor networks [2], wireless body networks [3], and wireless charging systems [4].

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Since Varshney first proposed the concept of simultaneous wireless information and power transfer (SWIPT) [5], this technique has attracted increasing interest. In [5], the authors investigated the fundamental tradeoff between the information transmission rate and power transfer. The SWIPT can provide a controllable and efficient allocation scheme of on-demand wireless information and energy [6].

The key of the SWIPT technology is the design of the receiver. The reason is because information reception and RF-EH work on very different power sensitivity (e.g., −10 dBm for energy harvesters versus −60 dBm for information receivers) [7]. In [7], due to the potential limitation that practical energy harvesting receivers are not yet able to decode information directly, the authors investigated two practical designs for the co-located receiver, namely, time switching (TS) and power splitting (PS). For the TS architecture, the receiver divides a time block into two parts, one for transmitting information and the other for harvesting energy. For the PS architecture, the receiver splits the received signal into two parts, one for transmitting information and the other for harvesting energy.

The existing research on the structure of the receiver is mostly based on TS or PS, and the research on the operation strategy of the receiver is mainly focused on single-input-single-output (SISO) channel. In [8], Liu L et al. studied the optimal switching strategy of EH/information decoding (ID) mode under a SISO channel subject to the time-varying interference. In [9], Zhou et al. summarized the strategy based on TS and PS as a dynamic PS strategy. This strategy dynamically splits the RF signal into two arbitrary proportion signal streams according to the change of the time.

The relaying technology can extend the coverage of communication. Combining the relaying technology with the SWIPT technology can further improve the performance of the system containing energy-constrained nodes. The relaying system based on SWIPT has also attracted the attention of scholars [10–15]. In [10], the authors studied a two-way decoding and forwarding relaying network based on the SWIPT technology, in which the relay is an energy-constrained node, but can obtain energy from the RF signals transmitted from the source node. Based on this network, the authors first analyzed the total information rate that could be achieved by the PS-based relaying transmission protocol, and then determined the PS ratio at the maximum total information rate, i.e., the optimal signal flow split ratio for EH and ID. In [11], the authors studied the outage probability of a cooperative network, in which the relay is a cooperative node capable of harvesting RF energy. The outage probabilities of amplify-and-forward (AF) and decode-and-forward (DF) were derived.

In this paper, we investigate the relaying energy allocation scheme in the multi-user SWIPT relaying system based on the TS operation strategy, in which a source transmits its signals to K $(K \geq 2)$ destinations via the help of an energy-constrained relay. The relay uses the energy harvested in the energy harvesting mode to decode, then amplify and forward the information of each user one by one. This paper will study the energy allocation scheme of the "total information rate maximization" model.

The rest of this paper is organized as follows. Section 2 describes the system model. Section 3 discusses the information rate of user. Section 4 discusses the energy allocation scheme and simulation. Finally, the conclusions are given in Sect. 5.

Notation: The notation $CN(0, N_0)$ denotes a circularly symmetric complex Gaussian random variable with zero mean and variance N_0. $\mathrm{E}[\cdot]$ and $|\cdot|$ denote the mathematical expectation and modulus value, respectively.

2 System Model

As shown in Fig. 1, this paper considers a multi-user SWIPT relaying system including a transmitter (Tx), a relay and K $(K \geq 2)$ receivers (Rx). The Tx and the Rx are equipped with single antenna. The relay is equipped with two antennas, one for receiving signals and the other for forwarding signals. It should be specially noted that the Tx and the Rx have energy supply devices, i.e., they have no energy limit. However, the relay has no energy supply devices, i.e., it is energy-constrained and operates by converting collected RF signals into electricity. The distance between the Tx and the relay is denoted as D_0, and the distance between the relay and the Rx of the i-th $(i = 1, \cdots, K)$ user is denoted as D_i.

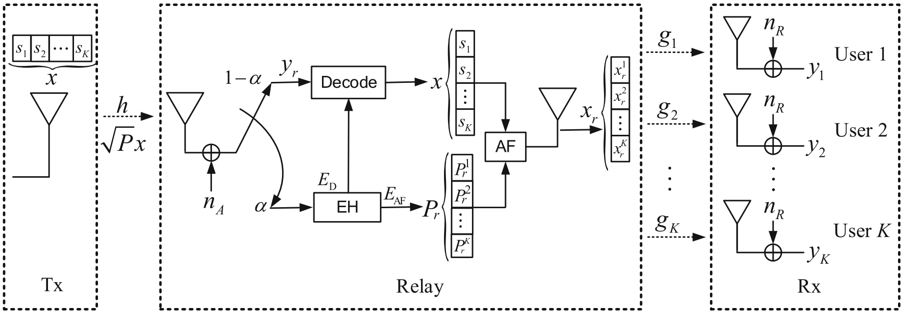


Fig. 1. System model

The Tx sends the information of all users to the relay. The relay decodes the received information, separates the information of each user, and then amplifies and forwards them to the receiver of each user. For the sake of discussion, we assume that the information of all users are correct after decoded and verified by the relay, and the relay will forward the information of all users. The receiver of the relay employs the TS strategy to receive signals. This paper considers a block-based transmission [16] of duration T. Thus, in the time of a transmission block, α proportion of time, i.e., αT, is used for EH, and $(1-\alpha)$ proportion of time, i.e., $(1-\alpha)T$, is used for information transmission. Correspondingly, the Tx transmits the energy signal (without the information of the user) within αT time, and the information signal (with the information of the user) within $(1-\alpha)T$ time. After completing the EH process of a transmission block, the relay uses a part of the harvested energy for the circuit consumption in the information decoding process and the remaining energy to amplify and forward the information of each user.

The working states of two antennas of the relay for the information signals are shown in Table 1. Except for the first transmission block at the beginning of communication, the information transmitted by the transmitting antenna is the information received by the receiving antenna in the previous transmission block. It is assumed that the amount of information at the relay is conserved, i.e., the transmitting module can forward the information processed by the receiving module in real time, and there will be no situation that the transmitting module has no information to send or the information is accumulated in the transmitting module. It can be achieved by adjusting the transmitting power of the Tx and the time slot switching coefficient at the relay. This paper will mainly study the information rate of the relay to the receiver of the user.

Table 1. Working states of the relay antennas for the information signals.

Transmission block	Receiving antenna	Transmitting antenna
1	Receive the information of transmission block 1	free
2	Receive the information of transmission block 2	Transmit the information of transmission block 1
3	Receive the information of transmission block 3	Transmit the information of transmission block 2
...	...	...

As shown in Fig. 1, the Tx sends signal x to the relay, and x contains information sent to all users. $s_i \ (i = 1, \cdots, K)$ is baseband signal, and represents the information sent to the i-th user. The RF band signal is expressed as $\sqrt{P}x$ with the average transmitting power P. y_r is the information signal received by the relay and n_A represents the noise introduced by the receiving antenna of the relay, $n_A \sim CN(0, \sigma_A^2)$. Before forwarding information, the relay decodes x and separates the information of each user. At the Rx side, the signal received by the i-th user is expressed as y_i. Similarly, n_R represents the noise introduced by the receiving antenna of the Rx, $n_R \sim CN(0, \sigma_R^2)$. The link from the Tx to the relay is referred to as the downlink with channel gain $h > 0$, and the link from the relay to the Rx of the i-th user is referred to as the uplink with channel gain $g_i > 0$.

3 Information Rate

As shown in Fig. 1, the information signal x transmitted by the Tx is expressed as

$$x = \sum\nolimits_{i=1}^{K} s_i \tag{1}$$

where x satisfies $\mathrm{E}[|x|^2] = 1$.

The information signal received by the relay is expressed as

$$y_r = \sqrt{h} \cdot \sqrt{P}x + n_A = \sqrt{hP} \cdot \sum\nolimits_{i=1}^{K} s_i + n_A \tag{2}$$

During a transmission block time, the energy harvested by the relay is expressed as

$$E_{\mathrm{EH}} = \eta h Q \cdot \alpha T \tag{3}$$

where η represents the energy conversion efficiency and Q represents the average power of the energy signal.

Defining the energy consumed by the relay for decoding information as E_{D} and the energy used for amplifying and forwarding signal as E_{AF}, we have

$$E_{\mathrm{EH}} = E_{\mathrm{D}} + E_{\mathrm{AF}} \tag{4}$$

This paper assumes that E_{D} is a fixed value, i.e., $E_{\mathrm{D}} = z \cdot \eta h Q T$, where z is a fixed coefficient, and $z \in (0, \alpha)$.

Figure 2 shows the time and energy allocation schematic of the relay in the multi-user relaying system. The receiving module of the relay harvests energy E_{EH} during αT time and receives information signal during $(1 - \alpha)T$ time. Decoding information consumes the energy E_{D}. After decoding, the AF energy E_{AF} is divided into K parts by the transmitting module in a block T to forward the information signal of each user. The energy proportion of the i-th user is expressed as τ_i. In addition, this paper assumes that the relay sends signals to the receiver of the user by time division multiple address (TDMA), i.e., a transmission block (T) is divided into K time slots and the relay forwards the amplified signals to each user one by one. For the sake of discussion, it is assumed that the relay averagely divides the time of a transmission block (T) according to the number of users (K), i.e., the time for the relay to forward information of each user is $t_i = T/K$.

Therefore, the amplification power of the i-th user information signal is

$$P_r^i = \frac{\tau_i \cdot E_{\mathrm{AF}}}{t_i} \tag{5}$$

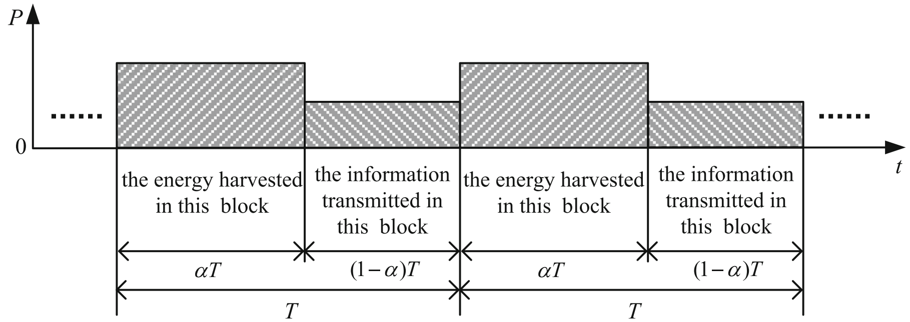
The energy allocation proportions τ_i meets the following conditions,

$$\sum\nolimits_{i=1}^{K} \tau_i \leq 1 \tag{6}$$

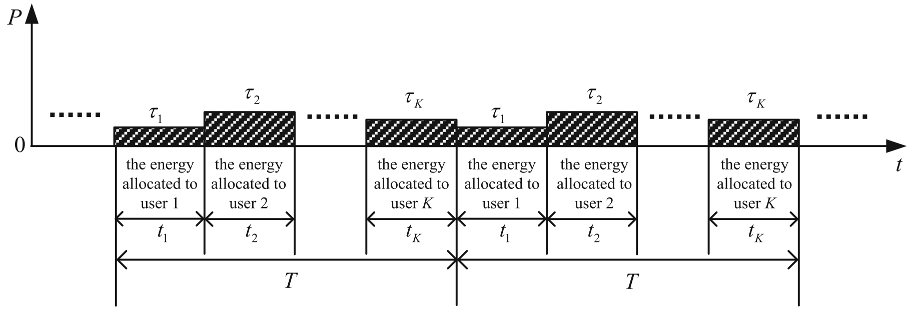
By substituting (3) and (4) into (5), we obtain

$$P_r^i = \frac{\tau_i \cdot \eta h Q T(\alpha - z)}{T/K} = \tau_i \cdot \eta h K Q(\alpha - z) \tag{7}$$

After amplification, the signal sent to the i-th user can be expressed as



(a) receiving module



(b) transmitting module

Fig. 2. Schematic of time and energy allocation

$$x_r^i = \sqrt{P_r^i} \cdot s_i = \sqrt{\tau_i \cdot \eta h K Q(\alpha - z)} \cdot s_i \tag{8}$$

The signal received by the *i*-th user from the relay can be expressed as

$$y_i = \sqrt{g_i} x_r^i + n_R = \sqrt{g_i \cdot \tau_i \cdot \eta h K Q(\alpha - z)} \cdot s_i + n_R \tag{9}$$

The signal to noise ratio (SNR) received by the *i*-th user is

$$SNR_i = \frac{\left(\sqrt{g_i \cdot \tau_i \cdot \eta h K Q(\alpha - z)}\right)^2}{\sigma_R^2} = \frac{g_i \cdot \tau_i \cdot \eta h K Q(\alpha - z)}{\sigma_R^2} \tag{10}$$

Therefore, the information rate of the *i*-th user receiving information is expressed as

$$R_i = \frac{1}{K} \cdot \log_2\left(1 + \frac{g_i \cdot \tau_i \cdot \eta h K Q(\alpha - z)}{\sigma_R^2}\right) = \frac{1}{K} \cdot \log_2(1 + \gamma_i \tau_i) \tag{11}$$

where $\gamma_i = \frac{g_i \eta h K Q(\alpha - z)}{\sigma_R^2}$.

4 Energy Allocation Scheme and Simulation

In (11), K and γ_i are the system parameters. The information rate of the user R_i can be viewed as a function of $\boldsymbol{\tau}$, and denoted as $R_i(\boldsymbol{\tau})$, where $\boldsymbol{\tau}$ represents the vector of energy allocation proportions, i.e., $\boldsymbol{\tau} = [\tau_1, \cdots, \tau_K]$.

Lemma: For any $i \in [1, \cdots, K]$, $R_i(\boldsymbol{\tau})$ is a convex function.

Proof: See Appendix A.

The total information rate of all users is denoted as $R_{sum}(\boldsymbol{\tau})$, as follows

$$R_{sum}(\boldsymbol{\tau}) = R_1(\boldsymbol{\tau}) + R_2(\boldsymbol{\tau}) + \cdots + R_K(\boldsymbol{\tau}) \tag{12}$$

The optimization problem P is established to obtain the optimal energy allocation scheme τ^* that maximizes the total information rate of all users.

$$\begin{aligned} \text{P}: \quad & \max_{\tau} \quad R_{sum}(\boldsymbol{\tau}) \\ & \text{s.t.} \quad \sum\nolimits_{i=1}^{K} \tau_i \leq 1, \\ & \qquad \tau_i \geq 0, \quad i = 1, 2, \cdots, K. \end{aligned}$$

Proposition: The vector of optimal energy allocation proportions is $\boldsymbol{\tau}^* = [\tau_1^*, \cdots, \tau_K^*]$, where

$$\tau_i^* = \frac{1}{K} - \frac{K-1}{K\gamma_i} + \frac{1}{K} \sum\nolimits_{\substack{j=1 \\ j \neq i}}^{K} \frac{1}{\gamma_j} \tag{13}$$

Proof: See Appendix B.

In practical application, $h \propto D_0^{-\kappa_{sr}}$ ($\propto$ represents a proportional relationship), $g_i \propto D_i^{-\kappa_{rd}}$, $i = 1, 2, \cdots, K$, where $\kappa_{sr} (\kappa_{sr} \geq 2)$ and κ_{rd} $(\kappa_{rd} \geq 2)$ represent the path fading index of the downlink and the uplink, respectively. Therefore, according to (11), we have $\gamma_i \propto hg_i$.

In this simulation, we set $K = 2$, $D_2 = 2D_1$, $\kappa_{sr} = \kappa_{rd} = 2$, so the relationship between γ_1 and γ_2 is

$$\frac{\gamma_1}{\gamma_2} = \frac{g_1}{g_2} = \left(\frac{D_2}{D_1}\right)^{\kappa_{rd}} = 4 \tag{14}$$

Further, for convenience, γ_1 and γ_2 is set to 22 dB and 16 dB, respectively.

Figure 3 shows the information rates of the users for different energy allocation proportions in a two-user SWIPT relaying system. It is observed that the information rate increases with the increase of the energy allocation proportion.

Figure 4 is the schematic of the total information rates of the system corresponding to different energy allocation proportions. As shown in Fig. 4, along the direction of the arrow, the total information rate of the system increases. This is because when $0 < \tau_1 + \tau_2 < 1$, the relay does not fully allocate the energy to all time slots. According to (11), for each user, R_i increases with the increase of τ_i, which it can also be seen in

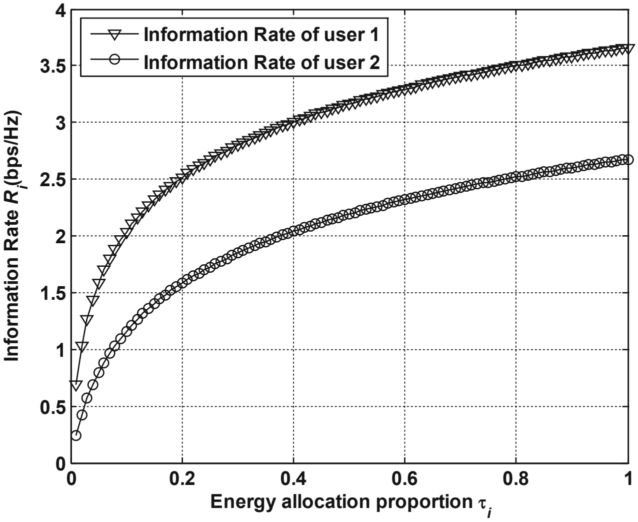


Fig. 3. Information rate (in bps/Hz) of the user versus energy allocation proportion

Fig. 3. Therefore, the maximum value of the total information rate of the system is obtained at $\tau_1 + \tau_2 = 1$. In Fig. 4, the point P represents the energy allocation proportions corresponding to the maximum total information rate of the system, i.e., $\boldsymbol{\tau}^* = [0.5094, 0.4906]$. At the optimal value $\boldsymbol{\tau}^*$, $R_{sum}(\boldsymbol{\tau}^*) = 5.356\,\text{bps/Hz}$; according to (11), $R_1(\boldsymbol{\tau}^*) = 3.176\,\text{bps/Hz}$ and $R_2(\boldsymbol{\tau}^*) = 2.180\,\text{bps/Hz}$.

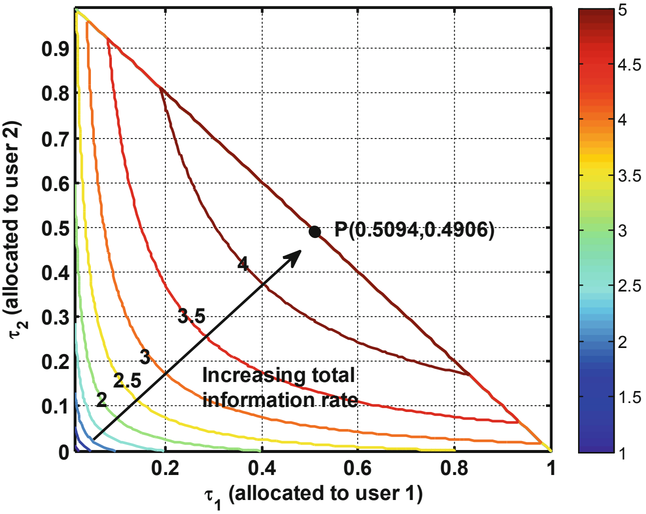


Fig. 4. Total information rate (in bps/Hz) versus energy allocation proportion

5 Conclusions

In this paper, we investigate the information rate of the user in the multi-user relaying system. The receiver of the relay employs the TS strategy to receive signals. The relay uses the energy harvested in the EH mode to decode, amplify and forward the information of each user. This paper studies the total information rate of user and proposes the energy allocation scheme corresponding to the maximum total information rate. Finally, the simulation diagram is drawn, and the effectiveness of the proposed scheme to improve the performance of the system is discussed according to the simulation diagram. In the further research, the energy allocation scheme that equates the information rates of all users will be proposed to avoid unfair among the users in the information rate.

6 Appendix A

Notation: $f^1(x)|_x$ represents the derivative of $f(x)$ with respect to x; $f^2(x)|_x$ denotes the derivative of $f^1(x)|_x$ with respect to x.

In (11), taking the first and second derivatives of $R_i(\boldsymbol{\tau})$ with respect to τ_i, we obtain

$$\nabla R_i(\boldsymbol{\tau}) = \frac{1}{K} \cdot \frac{1}{\ln 2} \cdot \frac{\gamma_i}{1 + \gamma_i \cdot \tau_i} \tag{15}$$

$$\nabla^2 R_i(\boldsymbol{\tau}) = \frac{1}{K} \cdot \frac{1}{\ln 2} \cdot \frac{-\gamma_i^2}{(1 + \gamma_i \cdot \tau_i)^2} \tag{16}$$

The Hessian matrix of $R_i(\boldsymbol{\tau})$ is defined as

$$\nabla^2 R_i(\boldsymbol{\tau}) = \left[d_{j,j}^{(i)} \right], \quad 1 \le j \le K \tag{17}$$

where $d_{j,j}^{(i)}$ represents the entry for row j, column j of $\nabla^2 R_i(\boldsymbol{\tau})$, and

$$d_{j,j}^{(i)} = \begin{cases} \frac{1}{K} \cdot \frac{1}{\ln 2} \cdot \frac{-\gamma_i^2}{(1 + \gamma_i \cdot \tau_i)^2} & , \quad j = i \\ 0 & , \quad \text{others} \end{cases} \tag{18}$$

For any real vector $v = [v_1, \cdots, v_K]^T$, we have

$$v^T \nabla^2 R_i(\boldsymbol{\tau}) v = \frac{1}{K \cdot \ln 2} \cdot \frac{-\gamma_i^2}{(1 + \gamma_i \cdot \tau_i)^2} \cdot v_i^2 \le 0 \tag{19}$$

i.e., $\nabla^2 R_i(\boldsymbol{\tau})$ is a negative semidefinite matrix for any i; therefore, $R_i(\boldsymbol{\tau})$ is a convex function of $\boldsymbol{\tau} = [\tau_1, \cdots, \tau_K]$.

7 Appendix B

The Lagrangian of the problem P can be expressed as

$$L_{sum}(\boldsymbol{\tau}, \upsilon) = R_{sum}(\boldsymbol{\tau}) - \upsilon\left(\sum\nolimits_{i=1}^{K} \tau_i - 1\right) \tag{20}$$

where υ represents the lagrangian multiplier. Taking the first derivative of $L_{sum}(\boldsymbol{\tau}, \upsilon)$ with respect to υ and τ_i, respectively, we have

$$L_{sum}(\boldsymbol{\tau}, \upsilon)^1|_{\upsilon} = \sum\nolimits_{i=1}^{K} \tau_i - 1 \tag{21}$$

$$L_{sum}(\boldsymbol{\tau}, \upsilon)^1|_{\tau_i} = \frac{\partial}{\partial \tau_i} R_{sum}(\boldsymbol{\tau}) - \upsilon, \quad i = 1, \cdots, K \tag{22}$$

Making $L_{sum}(\boldsymbol{\tau}, \upsilon)^1|_{\upsilon} = 0$ and $L_{sum}(\boldsymbol{\tau}, \upsilon)^1|_{\tau_i} = 0$, we have

$$\sum\nolimits_{i=1}^{K} \tau_i - 1 = 0 \tag{23}$$

$$\frac{1}{K} \cdot \frac{1}{\ln 2} \cdot \frac{\gamma_i}{1 + \gamma_i \cdot \tau_i} - \upsilon = 0, \quad i = 1, \cdots, K \tag{24}$$

According to (23), we can get

$$\sum\nolimits_{i=1}^{K} \tau_i = 1 \tag{25}$$

According to (24), we can get

$$\frac{\gamma_i}{1 + \gamma_i \cdot \tau_i} = K\upsilon \cdot \ln 2 = \text{constant} \tag{26}$$

So, we have

$$\frac{\gamma_1}{1 + \gamma_1 \cdot \tau_1} = \frac{\gamma_2}{1 + \gamma_2 \cdot \tau_2} = \cdots = \frac{\gamma_K}{1 + \gamma_K \cdot \tau_K} \tag{27}$$

According to $\frac{\gamma_1}{1 + \gamma_1 \cdot \tau_1} = \frac{\gamma_2}{1 + \gamma_2 \cdot \tau_2}$, we have

$$\tau_2 = \frac{1}{\gamma_1} - \frac{1}{\gamma_2} + \tau_1 \tag{28}$$

Similarly, we can obtain

$$\tau_i = \frac{1}{\gamma_1} - \frac{1}{\gamma_i} + \tau_1, \quad i = 2, \cdots, K \tag{29}$$

Combined with $\sum_{i=1}^{K} \tau_i = 1$, we can get

$$\tau_1 + \left(\frac{1}{\gamma_1} - \frac{1}{\gamma_2} + \tau_1 \right) + \cdots + \left(\frac{1}{\gamma_1} - \frac{1}{\gamma_K} + \tau_1 \right) = 1 \tag{30}$$

Further, we have

$$K\tau_1 + \frac{K-1}{\gamma_1} - \sum_{j=2}^{K} \frac{1}{\gamma_j} = 1 \tag{31}$$

So, we obtain

$$\tau_1 = \frac{1}{K} - \frac{K-1}{K\gamma_1} + \frac{1}{K} \sum_{j=2}^{K} \frac{1}{\gamma_j} \tag{32}$$

By substituting (32) into (28), we obtain

$$\tau_2 = \frac{1}{K} - \frac{K-1}{K\gamma_2} + \frac{1}{K} \sum_{\substack{j=1 \\ j \neq 2}}^{K} \frac{1}{\gamma_j} \tag{33}$$

Similarly, we can get

$$\tau_i = \frac{1}{K} - \frac{K-1}{K\gamma_i} + \frac{1}{K} \sum_{\substack{j=1 \\ j \neq i}}^{K} \frac{1}{\gamma_j}, \quad i = 1, \cdots, K \tag{34}$$

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