Communication

Not peer-reviewed version

Transmit Power Minimization in Multihop AF Relay Systems with Simultaneous Wireless Information and Power Transfer

Kunju Kim , Derek Kwaku Pobi Asiedu , Prince Anokye , Eunkyung Kim , Kyoung-Jae Lee *

Posted Date: 6 November 2023

doi: 10.20944/preprints202311.0358.v1

Keywords: multihop amplify-and-forward (AF) relays; power splitting (PS) ratio; simultaneous wireless information and power transfer (SWIPT)

Article

Transmit Power Minimization in Multihop AF Relay Systems with Simultaneous Wireless Information and Power Transfer

Kunju Kim [1], Derek Kwaku Pobi Asiedu [2], Prince Anokye[1], Eunkyung Kim [3] and Kyoung-Jae Lee [1,*]

[1] Department of Electronic Engineering, Hanbat National University, Daejeon, South Korea; golho2006@edu.hanbat.ac.kr; princeanokye@hanbat.ac.kr
[2] IMT Atlantique, Brest 29200, France; derek.asiedu@imt-atlantique.fr
[3] Department of Artificial Intelligence Software, Hanbat National University, Daejeon, South Korea; ekim@hanbat.ac.kr
* Correspondence: kyoungjae@hanbat.ac.kr; Tel.: +82-42-821-1730

Abstract: This paper studies a multihop amplify-and-forward (AF) simultaneous wireless information and power transfer (SWIPT) relaying system. Each relaying node harvests energy using power splitting (PS) scheme from a part of its received signal to amplify and forward the rest the received signal to the next relay. Based on this system model and signal flow, we derived and solved the convex energy minimization problem with optimal PS ratio. The influence of processing cost was then investigated for the AF-SWIPT system with the decode-and-forward SWIPT as benchmark, where AF-SWIPT was found to be superior.

Keywords: multihop amplify-and-forward (AF) relays; power splitting (PS) ratio;simultaneous wireless information and power transfer (SWIPT)

---

1. Introduction

The Internet-of-Things (IoT) connects network-enabled devices communicating with each other over the Internet. Hence, the objective of IoT is to integrate the physical world and the virtual world to attain a self-sustaining system [1]. Currently, research into the application of IoT for the creation of smart-cities, smart-homes, smart-energy, intelligent-transportation system, and many more is growing. An IoT network consists of the use of routing schemes, a gateway supporting communication between the different nodes and a central system [1]. These routing schemes facilitate either direct or relaying communication between a gateway and a particular node. The routing/relaying nodes can be opportunistically implemented by non-active user devices [1]. This results in the selected user nodes consuming their power in facilitating communication between the two user pairs [2,3]. This implies that, the selected users sacrifice their resources to facilitate relaying procedures [2,11]. The strain on the relay nodes can be mitigated by employing wireless power transfer (WPT) [1–3].

Recently, research into alternative wireless sources (e.g., radio frequency (RF) and light energy harvesting) of energy to power IoT devices is also increasing [1–6]. Such alternative wireless power sources are on the market, e.g., wi-charge technology (the wi-charger devices), Pi charger, energous RF chargers and Warp RF wireless charging systems. From literature, WPT using RF can be accomplished by using two different techniques, namely, simultaneous wireless information and power transfer (SWIPT), and wireless powered communication network (WPCN) [1–3,5]. SWIPT involves the transmission of wireless information signal and wireless power signal concurrently [1–3,5]. Time switching (TS) and power splitting (PS) are the two main techniques in order to implement SWIPT [1–3]. The successive transmission of wireless information signal and wireless power signal is used to accomplish WPCN [1–3].

Research on RF-based WPT has evolved from point-to-point systems, dual-hop cooperative systems to multi-hop cooperative systems. A few literature on both dual-hop and multi-hop

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 6 November 2023 doi:10.20944/preprints202311.0358.v1

cooperative systems can be found in [1–9]. In this paper, we extend the work in [1] which focused on a decode-and-forward (DF)-SWIPT multihop system model to an amplify-and forward (AF)-SWIPT multi-hop system model. Similar to the work in [1], we consider single-antenna nodes, SWIPT PS mode at each relay node, and the optimization problem on energy efficiency. Finally, the closed-form solution are obtained for our optimization problem. In the simulation results, we compare AF-SWIPT multi-hop systems to the DF-SWIPT in [1].

The rest of the paper is organized as follows, Sections 2, 3, and 4 contains the the stepwise process in formulating the AF-SWIPT multi-hop optimization problem, the solutions for our optimization problem, and simulation results and discussion, respectively. Finally, concluding remarks are provided in Section 5.

2. System Model and Problem Formulation

The IoT network consists of the source node, K AF-SWIPT relays, and the destination node, are shown in Figure 1. Each node has a single antenna. The source is a base station (BS) which may consist of the data gateway and the external/central systems of the IoT network [11–13,15–17]. In order to increase the operation efficiency of the relay node, each relay node operates in SWIPT mode. A RF signal received at each relay is split using the PS ratio where a part of the signal is stored in battery in each relay via energy harvesting (EH). Then, the information processing (i.e., amplification and forwarding) is performed using the remaining RF signals, and then the transmission is performed to the next node with the harvested energy.

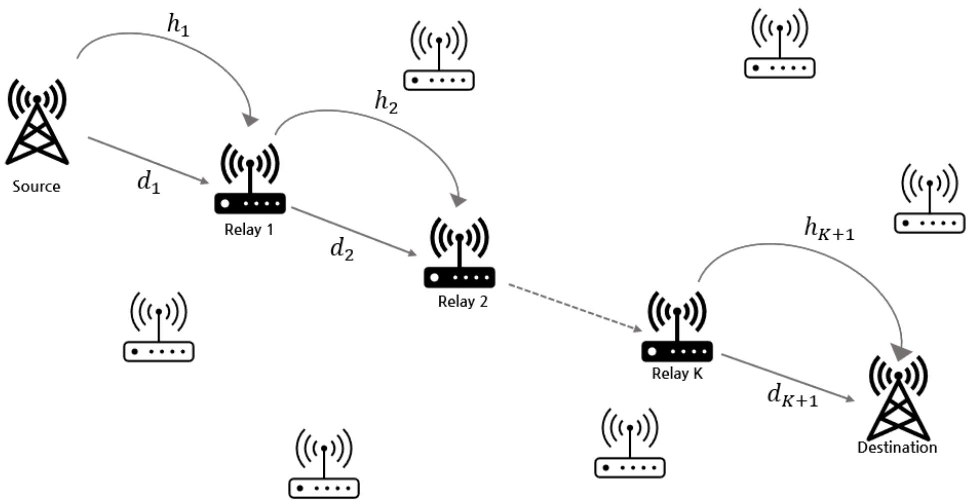

Figure 1. Multihop AF relay systems with SWIPT architecture.

The structure of our AF-SWIPT relay is shown in Figure 2. Each relay has a battery, which can store energy and perform retransmission using it. Each AF-SWIPT relay performs EH using a power splitting (PS) scheme and operates in half-duplex mode.

We assume that the source node provides the channel state information (CSI) for all communication nodes. However, each relay and the destination node only knows the CSI for their communication channel. It is assumed that there is no direct link between the current node and the next second or more nodes. For example, there is no direct link between the first node and the third node.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 6 November 2023 doi:10.20944/preprints202311.0358.v1

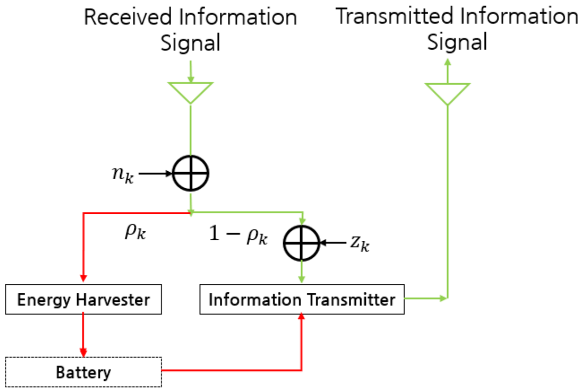

Figure 2. Multihop AF relay node SWIPT architecture.

The received RF signal at node $k, \forall k = 1 \cdots, K+1$ from the previous node is given as

$$y_k = h_k x_{k-1} + n_k \tag{1}$$

where h_k is the channel coefficient between the current node and the previous node, and $n_k \sim CN(0,\delta_k^2)$ represents the antenna noise at the current node. The channel h_k is defined as $h_k = \sqrt{\zeta_k}\tilde{h}_k$, where $\zeta_k = G_k(d_k/d_0)^{-\alpha_k}$ is the large-scale fading coefficient, G_k is the attenuation constant for a distance d_0, α_k is the pathloss exponent, d_k is distance between the transmit and receive nodes and $\tilde{h}_k \sim CN(0,1)$ is the Rayleigh fading component. Next, the signal for EH and harvested energy at the kth relay node are written, respectively, as

$$y_k^{EH} = \sqrt{\rho_k} y_k \tag{2}$$

$$E_k = \beta_k \rho_k \left|h_k\right|^2 E_{k-1} \tag{3}$$

$$E_{K+1} = \beta_{K+1}\rho_{K+1}\left|h_{K+1}\right|^2 E_K - P_c \tag{4}$$

where P_c is the processing power for information decoding at destination node, E_0 is the transmit energy at source node, and signal for information transmission at the kth relay is represented by

$$y_k^{TR} = \sqrt{1-\rho_k} y_k + z_k \tag{5}$$

where $z_k \sim CN(0,\sigma_k^2)$ is the additional noise introduced by the information decoding (ID) circuitry. The signal-to-noise ratio (SNR) is expressed as

$$\gamma_k = \frac{\prod_{j=1}^{k-1}\beta_j\rho_j\prod_{j=1}^{k}(1-\rho_j)\left|h_j\right|^2 E_0}{\sum_{i=1}^{k}[((1-\rho_i)\delta_i^2+\sigma_i^2)\prod_{j=i}^{k-1}\beta_j\rho_j\prod_{j=1,j\neq i}^{k}(1-\rho_j)\prod_{j=i+1}^{k}\left|h_j\right|^2]} \tag{6}$$

The signal to be transmitted to the kth relay is represented by

$$x_k = g_k y_k^{TR} \tag{7}$$

where $g_k \approx \sqrt{\frac{E_k}{(1-\rho_k)E_{k-1}\left|h_j\right|^2}} = \sqrt{\frac{\beta_k\rho_k}{1-\rho_k}}$ is amplification factor, and x_0 is the information signal at source node.

 doi:10.20944/preprints202311.0358.v1

We now consider the problem of optimizing the PS ratio $\{\rho_k\}_{k=1}^{K}$ at the relay nodes and energy at the source node E_0. We aim to minimize the source transmit power, under the SNR of destination node constraint and PS ratio for each of the multihop links as

$$\begin{aligned} \min_{E_0,\{\rho_k\}_{k=1}^{K}} \quad & E_0 \\ \text{subject to} \quad & \gamma_{K+1} \geq \bar{\gamma}_{K+1} \\ & 0 \leq \rho_k \leq 1, \quad k = 1, \cdots, K+1 \\ & E_0 \geq 0 \end{aligned} \tag{8}$$

The solution to the above problem is provided in the following section, and the induction process will be attached to the Appendix A.

3. Problem Solution

In this section, we provide the solution of source transmit power minimization problem. The optimal transmit energy at the source node is expressed to

$$E_0 = \bar{\gamma}_{K+1} \frac{\sum_{i=1}^{K+1}[((1-\rho_i)\delta_i^2 + \sigma_i^2)\prod_{j=i}^{K}\beta_j\rho_j\prod_{j=1,j\neq i}^{K+1}(1-\rho_j)\prod_{j=i+1}^{K+1}|h_j|^2]}{\prod_{j=1}^{K}\beta_j\rho_j\prod_{j=1}^{K+1}(1-\rho_j)\,|h_j|^2} \tag{9}$$

where $\bar{\gamma}_{K+1}$ is the SNR threshold constraint of the destination node. The optimal PS ratio at the kth node is written as

$$\rho_k = \frac{C_k + \sum_{i=k+1}^{K} D_i - \sqrt{F_k[\sum_{i=k+1}^{K+1} D_i]}}{C_k + \sum_{i=k+1}^{K} D_i - F_k}, \qquad k = 1, \cdots, K \tag{10}$$

where C_k, D_i, and F_k are defined as

$$C_k = ((1-\rho_{K+1})\delta_{K+1}^2 + \sigma_{K+1}^2)\prod_{j=k}^{K}(1-\rho_{j+1}) \tag{11}$$

$$D_i = ((1-\rho_i)\delta_i^2 + \sigma_i^2)\prod_{j=i}^{K}\beta_j \prod_{j=k+1,j\neq i}^{K+1}(1-\rho_j)\prod_{j=i}^{K}\rho_j\,|h_{j+1}|^2 \tag{12}$$

$$F_k = \prod_{j=k}^{K}\beta_j \prod_{j=k+1}^{K+1}(1-\rho_j)\,|h_j|^2 \prod_{j=k+1}^{K}\rho_j\sigma_k^2 \tag{13}$$

4. Simulation Results

This section evaluates the performance of the AF-SWIPT system compared with the DF-SWIPT system as benchmark [1]. For the large-scale fading component, the attenuation constant $G_0 = -10$ dB, and the pathloss exponent $\alpha = 3$ are assumed. The distance between each node is $d = d_1 = \cdots = d_K = 2$ m, the antenna noise variance $\sigma^2 = \sigma_1^2 = \cdots = \sigma_{K+1}^2 = -80$ dBm, and the energy conversion efficiency $\beta = \beta_1 = \cdots = \beta_K = 0.7$. We asuume that $P_c = 0$ at destination node, because the destination node are received the enough power for decoding to the previous node. The PS ratio used for the suboptimal scheme is $\rho_k = 0.5$. The simulation results are obtained over 10^4 random channel realizations.

Figure 3 shows the effect of each relay circuit power P_c on E_0. When P_c is low, the effect on E_0 is insignificant, but as P_c increases, E_0 also increases. Unlike AF-SWIPT, where signals are decoded only

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 6 November 2023 doi:10.20944/preprints202311.0358.v1

at destination nodes, DF-SWIPT has a larger of E_0 value because signals are decoded at all relay nodes before they are re-transmission.

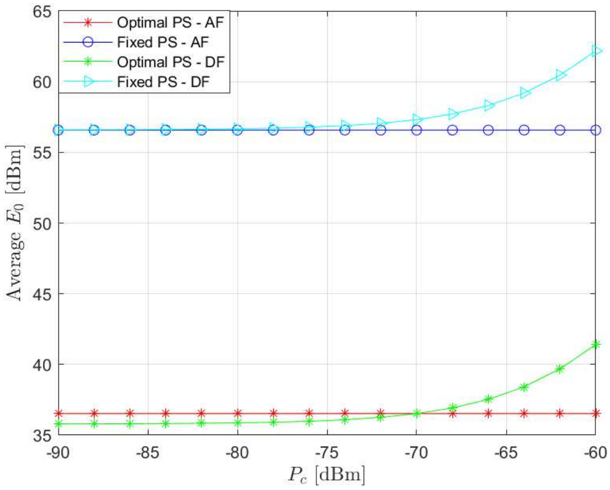

Figure 3. The influence of increasing each relay P_c ($K = 3, \bar{\gamma} = -5$ dB).

A simulation result based on the influence of increasing number of relays, K, follows in Figure 4. Figure 4 shows that E_0 increases as the number of relays. The influence of P_c affects all the relays. It is observed that, the AF-SWIPT system has a lower E_0 than the DF-SWIPT system. This is because there is no signal decoding (i.e., processing power) at the relays for AF-SWIPT, unlike in the DF-SWIPT. In the AF-SWIPT signal decoding occurs only at the destination. Therefore, processing power is used only at the destination for the AF-SWIPT, while processing power is used at all nodes in the DF-SWIPT.

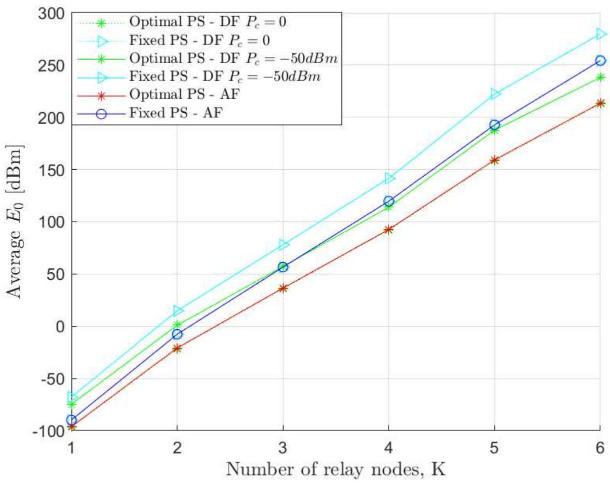

Figure 4. Average E_0 against the number of relay nodes at $\bar{\gamma} = -5$ dB, $P_c = -50$ dBm.

Figure 5 shows a plot of the average E_0 versus the SNR threshold constrain $\bar{\gamma}$ (in dB). The optimal PS scheme shows a lower E_0 value than the suboptimal PS scheme. When $\bar{\gamma}$ is low, E_0 is very high, which seems to have a great influence on the $\bar{\gamma}$ with a low P_c influence.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 6 November 2023 doi:10.20944/preprints202311.0358.v1

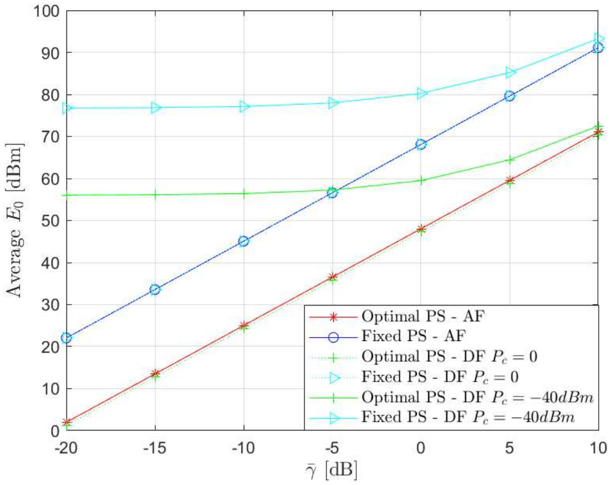

Figure 5. Average E_0 relative to $\bar{\gamma}$ at $K = 3, P_c = -50$ dBm.

Figure 6 shows the E_0 against the internode distance, d_k. As d_k increases, more transmission power is required.

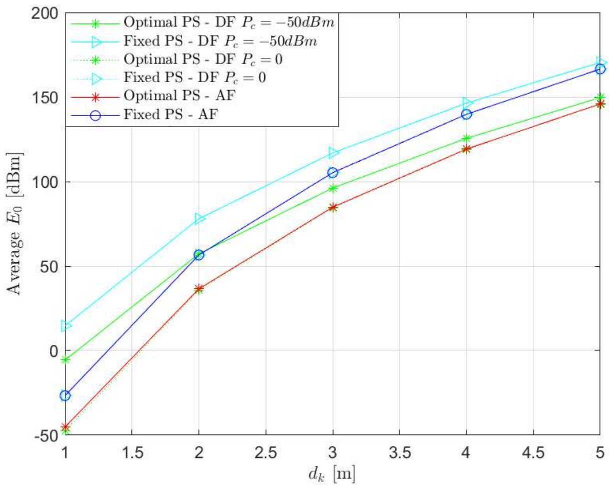

Figure 6. Average E_0 relative to $\bar{\gamma}$ at $K = 3, P_c = -50$ dBm.

5. Conclusion

This paper investigated on the AF-SWIPT multi-hop cooperative relaying in IoT networks. Depending on the decoding cost, the AF-SWIPT system is more efficient compared to DF-SWIPT for data relaying. The AF-SWIPT source energy minimization optimization problem is presented in this paper. The idea is to promote energy efficiency through signal transmission energy cost. Simulation results showed the AF-SWIPT has better energy efficiency in terms of decoding cost compared to the DF-SWIPT. Possible extensions of this research are in the area of implementing the time-switching SWIPT protocol, MIMO multi-hop systems, WPCN multi-hop networks and development of routing algorithms for the multi-hop wireless powered networks.

Author Contributions: Conceptualization Asiedu, D.K.P.; Methodology, Original Draft Preparation and Writing Kim, K.J.; Review and editing Prince, A. and Kim, E; Supervision, Lee, K.-J..

Appendix A

The problem 8 is nonconvex with respect to E_0 and $\{\rho_k\}_{k=1}^{K}$. By changing the problem, we rewrite problem 8 into and equivalent convex problem.

 doi:10.20944/preprints202311.0358.v1

$$\begin{aligned} \min_{Q,\{\rho_k\}_{k=1}^{K}} \quad & 1/Q \\ \text{subject to} \quad & \gamma_{K+1} \geq \bar{\gamma}_{K+1} \\ & 0 \leq \rho_k \leq 1, \quad k = 1, \cdots, K+1 \\ & Q \geq 0 \end{aligned} \tag{A1}$$

where $Q = (1/E_0)$. The Lagrangian of the problem A1 is defined with its KKT conditions given as

$$L\{Q, \lambda\} = \frac{1}{Q} + \lambda \left(\bar{\gamma}_{K+1} - \frac{\prod_{j=1}^{K} \beta_j \rho_j \prod_{j=1}^{K+1} (1-\rho_j) |h_j|^2}{Q \sum_{i=1}^{K+1} [((1-\rho_i)\delta_i^2 + \sigma_i^2) \prod_{j=i}^{K} \beta_j \rho_j \prod_{j=1, j\neq i}^{K+1} (1-\rho_j) \prod_{j=i+1}^{K+1} |h_j|^2]} \right) \tag{A2}$$

$$\begin{aligned} \frac{\partial L}{\partial Q} = & -\frac{1}{Q^2} \\ & + \lambda \left(\bar{\gamma}_{K+1} + \frac{\prod_{j=1}^{K} \beta_j \rho_j \prod_{j=1}^{K+1} (1-\rho_j) |h_j|^2}{Q^2 \sum_{i=1}^{K+1} [((1-\rho_i)\delta_i^2 + \sigma_i^2) \prod_{j=i}^{K} \beta_j \rho_j \prod_{j=1, j\neq i}^{K+1} (1-\rho_j) \prod_{j=i+1}^{K+1} |h_j|^2]} \right) = 0 \end{aligned} \tag{A3}$$

$$\lambda \left(\bar{\gamma}_{K+1} - \frac{\prod_{j=1}^{K} \beta_j \rho_j \prod_{j=1}^{K+1} (1-\rho_j) |h_j|^2}{Q \sum_{i=1}^{K+1} [((1-\rho_i)\delta_i^2 + \sigma_i^2) \prod_{j=i}^{K} \beta_j \rho_j \prod_{j=1, j\neq i}^{K+1} (1-\rho_j) \prod_{j=i+1}^{K+1} |h_j|^2]} \right) = 0 \tag{A4}$$

From A3, we can calculate λ as

$$\lambda = \frac{\sum_{i=1}^{K+1} [((1-\rho_i)\delta_i^2 + \sigma_i^2) \prod_{j=i}^{K} \beta_j \rho_j \prod_{j=1, j\neq i}^{K+1} (1-\rho_j) \prod_{j=i+1}^{K+1} |h_j|^2]}{\prod_{j=1}^{K} \beta_j \rho_j \prod_{j=1}^{K+1} (1-\rho_j) |h_j|^2} \tag{A5}$$

and substituting A5 into A3,

$$\frac{1}{Q} = \bar{\gamma}_{K+1} \frac{\sum_{i=1}^{K+1} [((1-\rho_i)\delta_i^2 + \sigma_i^2) \prod_{j=i}^{K} \beta_j \rho_j \prod_{j=1, j\neq i}^{K+1} (1-\rho_j) \prod_{j=i+1}^{K+1} |h_j|^2]}{\prod_{j=1}^{K} \beta_j \rho_j \prod_{j=1}^{K+1} (1-\rho_j) |h_j|^2} \tag{A6}$$

Next, we change the problem A1 to find the optimal PS ratio as

$$\begin{aligned} \min_{x,y,\{\rho_k\}_{k=1}^{K}} \quad & \frac{x^2}{y} \\ \text{subject to} \quad & \bar{\gamma}_{K+1} \sum_{i=1}^{K+1} [((1-\rho_i)\delta_i^2 + \sigma_i^2) \prod_{j=i}^{K} \beta_j \rho_j \prod_{j=1, j\neq i}^{K+1} (1-\rho_j) \prod_{j=i+1}^{K+1} |h_j|^2] \geq x^2 \\ & \prod_{j=1}^{K} \beta_j \rho_j \prod_{j=1}^{K+1} (1-\rho_j) |h_j|^2 \geq y \end{aligned} \tag{A7}$$

and we formulate the Lagrangian of changed problem A7 to

$$L\left\{x,y,\{\rho_k\}_{k=1}^{K},\lambda_1,\lambda_2\right\} = \frac{x^2}{y}+ \lambda_1\left(x^2-\bar{\gamma}_{K+1}\sum_{i=1}^{K+1}\left[((1-\rho_i)\delta_i^2+\sigma_i^2)\prod_{j=i}^{K}\beta_j\rho_j\prod_{j=1,j\neq i}^{K+1}(1-\rho_j)\prod_{j=i+1}^{K+1}|h_j|^2\right]\right) + \lambda_2\left(y-\prod_{j=1}^{K}\beta_j\rho_j\prod_{j=1}^{K+1}(1-\rho_j)\,|h_j|^2\right) \quad \text{(A8)}$$

The KKT conditions are represented as

$$\frac{\partial L}{\partial \rho_k} = \bar{\gamma}_{K+1}\left(-\delta_k^2 A_k - \sum_{i=k+1}^{K+1} B_i\frac{1}{\rho_k} + B_k\frac{1}{1-\rho_k}\right) = 0,\quad k=1,\ldots,K \quad \text{(A9)}$$

where A_k and B_k are defined as bellows

$$A_k = \frac{1}{\prod_{j=1}^{k-1}\beta_j\rho_j(1-\rho_j)\prod_{j=1}^{k}|h_j|^2} \quad \text{(A10)}$$

$$B_k = ((1-\rho_k)\delta_k^2+\sigma_k^2)A_k \quad \text{(A11)}$$

From A9, we can find the each optimal PS ratios to

$$\rho_k = \frac{C_k+\sum_{i=k+1}^{K}D_i-\sqrt{F_k[\sum_{i=k+1}^{K+1}D_i]}}{C_k+\sum_{i=k+1}^{K}D_i-F_k},\qquad k=1,\cdots,K \quad \text{(A12)}$$

$$\rho_{K+1}=0 \quad \text{(A13)}$$

where the constants C_k, D_i, and F_k are defined as

$$C_k = ((1-\rho_{K+1})\delta_{K+1}^2+\sigma_{K+1}^2)\prod_{j=k}^{K}(1-\rho_{j+1}) \quad \text{(A14)}$$

$$D_i = ((1-\rho_i)\delta_i^2+\sigma_i^2)\prod_{j=i}^{K}\beta_j\prod_{j=k+1,j\neq i}^{K+1}(1-\rho_j)\prod_{j=i}^{K}\rho_j\,|h_{j+1}|^2 \quad \text{(A15)}$$

$$F_k = \prod_{j=k}^{K}\beta_j\prod_{j=k+1}^{K+1}(1-\rho_j)\,|h_j|^2\prod_{j=k+1}^{K}\rho_j\sigma_k^2 \quad \text{(A16)}$$

References

1. Asiedu, D. K. P.; Lee, H.; Lee, K.-J. Simultaneous wireless information and power transfer for decode-and-forward Multihop Relay systems in energy-constrained IoT networks. *IEEE Internet Things J.* **2019**, *6*, 9413-9426.
2. Mahama, S.; Asiedu, D. K. P.; Lee, K.-J. Simultaneous wireless information and power transfer for cooperative relay networks with battery. *IEEE Access* **2017**, *5*, 13171–13178.
3. Asiedu, D. K. P.; Mahama, S.; Jeon, S.-W.; Lee, K.-J. Optimal power splitting for simultaneous wireless information and power transfer in amplify-and-forward multiple-relay systems. *IEEE Access* **2018**, *6*, 3459–3468.

 doi:10.20944/preprints202311.0358.v1

4. Lee, H.; Lee, K.-J.; Kim, H.; Lee, I. Joint transceiver optimization for MISO SWIPT systems with time switching. *IEEE Trans. on Wireless Commun.* **2018**, *17*, 3298–3312.
5. Lee, H.; Lee, K.-J.; Kim, H.; Lee, I. Wireless information and power exchange for energy-constrained device-to-device communications. *IEEE Internet Things J.* **2018**, *5*, 3175–3185.
6. Clerckx, B.; Zhang, R.; Schober, R.; Ng, D. W. K.; Kim, D. I.; Poor, H. V. Fundamentals of wireless information and power transfer: From RF energy harvester models to signal and system designs. *IEEE Journal on Selected Areas in Communications* **2018**, *37*, 4–33.
7. He, S.; Xie, K.; Chen, W.; Zhang, D.; Wen, J. Energy-aware routing for SWIPT in multi-hop energy-constrained wireless network. *IEEE Access* **2018**, *6*, 17996–18008.
8. Liu, X.; Wen, Z.; Liu, D.; Zou, J.; Li, S. Joint source and relay beamforming design in wireless multi-hop sensor networks with SWIPT. *Sensors* **2019**, *19*, 182.
9. Djiroun, F. Z.; Djenouri, D. Mac protocols with wake-up radio for wireless sensor networks: A review. *IEEE Commun. Surveys & Tutorials* **2017**, *19*, 587–618.
10. Zhang, Z.; Pang, H.; Georgiadis, A.; Cecati, C.; Wireless power transfer - an overview. *IEEE Trans. Indust. Elect.* **2018**, *66*, 1044– 1058.
11. Ciuonzo, D.; Rossi, P. S.; Dey, S. Massive MIMO channelaware decision fusion. *IEEE Trans. Signal Process.* **2015**, *63*, 604–619.
12. Rossi, P. S.; Ciuonzo, D.; Kansanen, K.; Ekman, T. Performance analysis of energy detection for MIMO decision fusion in wireless sensor networks over arbitrary fading channels. *IEEE Trans. Wireless Commun.* **2016**, *15*, 7794–7806.
13. Raghavendra, C. S.; Sivalingam, K. M.; Znati, T. *Wireless Sensor Networks.*; Publisher: Springer USA, New York, 2006.
14. Mao, M.; Cao, N.; Chen, Y.; Zhou, Y. Multi-hop relaying using energy harvasting. *IEEE Wirless Commun. Letters* **2015**, *4*.
15. Sabor, N.; Sasaki, S.; Abo-Zahhad, M.; Ahmed, S. M. A comprehensive survey on hierarchical-based routing protocols for mobile wireless sensor networks: Review, taxonomy, and future directions. *Wireless Commun. Mobile Comput.* **2017**, *2017*, Art. no. 2818542.
16. Djiroun, F. Z.; Djenouri, D. MAC protocols with wake-up radio for wireless sensor networks: A review. *IEEE Commun. Surveys Tuts.* **2017**, *19*, 587–618.
17. Sandeep, D. N.; Kumar, V. Review on clustering, coverage and connectivity in underwater wireless sensor networks: A communication techniques perspective. *IEEE Access* **2017**, *5*, 11176–11199.