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Energy-Aware Routing for SWIPT in Multi-Hop Energy-Constrained Wireless Network

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ABSTRACT Simultaneous wireless information and power transfer (SWIPT) transmits information and powers wireless nodes with the same radio frequency signal. It can prolong the life time of the energy-constrained wireless nodes. Current works of SWIPT focus on one-hop and two-hop wireless network. In order to verify the performance of SWIPT in multi-hop energy-constrained wireless network (MECWN) where the energy harvested by the receiver node can be as an energy compensation for data forwarding, this paper concurrently considers SWIPT and routing selection in MECWN. To reduce the energy consumption, we first formulate the information and energy allocation problem of link in a forwarding path, which is dependent on the next-hop node, and solve it by an iterative allocation algorithm. A novel routing metric evaluates the energy consumption of link transmitted with or without SWIPT. The energy-aware SWIPT routing algorithm allocates the information and energy of link with allocation algorithm during path finding process. To the best of our knowledge, this is the first solution that takes account of SWIPT and routing in MECWN. Our performance studies demonstrate that our proposed algorithms can effectively exploit those node resources whose energy are not enough and significantly decrease the energy consumption.

INDEX TERMS Simultaneous wireless information and power transfer, multi-hop energy-constrained wireless network, resource allocation, routing algorithm, network energy.

I. INTRODUCTION

As a new wireless communication technology, simultaneous wireless information and power transfer (SWIPT) [1] takes full advantage of the available wireless resources and provides an attractive solution to prolong the life time of the energy-constrained wireless node and wireless networks (equipped with batteries), such as wireless sensor networks and mobile sensing networks.

SWIPT is benefit from the radio frequency (RF)-based wireless power transfer technology where the receiver captures the ambient RF signals and converts it into a direct current (DC) voltage by special circuits (rectennas) [2]. Since the RF signals convey energy and can be information carrier at the same time, SWIPT transmits information and reliably powers wireless nodes with the RF signals. Compared with RF-based wireless power transfer, besides the ambient interfering signals, the desired information signals can be also harvested by the receiver in SWIPT. With the help of the splitting mechanisms [3]–[5], the receiver can harvest energy and decode information from the same RF signal transmitted by a sender.

Obviously, SWIPT will have deep influence on the design of energy-constrained wireless network, whose advantages are as follows: (1) it provides more reliable energy from controllable RF, compared with natural dynamic sources, such as solar and wind; (2) the wireless node can still sense, send and receive packet when harvesting energy with SWIPT [6], [7].

After addressing the architecture design issue [3]–[5], current works of SWIPT generally focus on the application in one-hop and two-hop wireless network scenario. Assuming that the network nodes are in one-hop [8]–[22] or two-hop [23]–[32] wireless networks, most of them only take account of the information and energy allocation problem to decide how many percent of received power is used to decode information or harvest energy for better performance, such as higher throughput, more harvested power/energy and less transmission power. Reference [33] starts to apply SWIPT to a multi-hop mobile wireless sensor network and shows that compared with no energy harvesting, by SWIPT, the nodes have more remaining energy and the remaining energy among nodes is more balanced.

In multi-hop energy-constrained wireless network (MECWN) with SWIPT, the energy harvested by the receiver node can be as a energy compensation for data forwarding. SWIPT can balance energy distribution and prolong the lifetime of MECWN. However, when SWIPT is applied in MECWN, each hop node needs to allocate the optimal information and energy, and the different allocation of information and energy affects the network topology and the route selection, which is challenge. Some of the challenges are as follows.

First, the end-to-end path includes multi-hops in multi-hop energy-constrained wireless network, and each hop needs to allocate the information and energy. To minimize the end-to-end transmission power, the information and energy allocation of each hop needs to be considered in the path totally. The next-hop and past-hop may affect the information and energy allocation while a link is in a forwarding path.

Second, the information and energy allocation affects the neighbor node set and network topology, which further decides the routing selection. The neighbor node set is changed as the change of information and energy allocation.

Third, compared with the information transmissions (IT) where the entire signal is used to decode information without energy harvesting, SWIPT makes the routing more complicated. In MECWN with SWIPT, there are two transmission modes among nodes, SWIPT and IT. Which transmission mode of link may produce better performance? It desires careful design to choose the transmission mode along with the routing path and allocate information and energy.

In general, routing, information and energy allocation, and transmission mode chosen are inter-dependent. To enable SWIPT in MECWN and fulfill the full potential of both techniques, these problems need to be systematically solved together.

In order to verify the performance of SWIPT in multi-hop energy-constrained wireless network, this paper concurrently considers SWIPT and routing selection in multi-hop energy-constrained wireless network. To select the next-hop and path, we propose an allocation algorithm of information and energy, a novel energy cost routing metric, and an energy-aware SWIPT routing algorithm. The main contributions of this work can be summarized as follows.

- We introduce the information and energy allocation problem for SWIPT when the link is in a path and the receiver node needs to forward, and formulate it as an allocation model. Based on the allocation model, an iterative information and energy allocation algorithm (IEA) is proposed to solve the allocation problem.
- We propose a novel energy cost (Ecost) metric which evaluates the link energy consumption with two different transmission modes (IT and SWIPT), and chooses a better transmission mode. Based on the metric, we introduce an energy-aware SWIPT routing algorithm (ESWIPTR) which allocates the information and energy of link by IEA algorithm during finding path.
- We design a distributed synchronous proactive protocol and an asynchronous proactive table-driven protocol for ESWIPTR.
- Extensive simulations have been carried out, which demonstrate that our solution is effective and incorporating SWIPT in multi-hop networks can achieve the significant energy cost gains.

The remainder of this paper is organized as follows. The related works are reviewed in section II. Section III introduces the IT and SWIPT models, a motivation example and solution overview. The detailed formulation and algorithm of information and energy allocation problem are presented in Sections IV, and routing algorithm is designed in Section V. Section VI provides simulation results and analysis to compare the performance of our solution. In the end, we conclude this work in Section VII.

Notations: scalars and vectors are denoted by lower-case letters and bold-face lower-case letters, respectively. $E[x]$ and $|x|$ denote the statistical expectation and the absolute value of a vector x, respectively. $\mathcal{CN}(\mu, \sigma^2)$ denotes the circularly symmetric complex Gaussian (CSCG) distribution with mean μ and variance σ^2, and '$\sim$' stands for "distributed as."

II. RELATED WORKS

SWIPT provides not only wireless data but also energy accesses simultaneously to mobile nodes, whose potential has been first presented in [1]. However, independent decoding information and harvesting energy from the same received signal is hard to be realized in existing receiver circuits. Therefore, several studies have considered the architecture design of receivers [3]–[5], which introduce two practical information energy splitting mechanisms in receiver: i) time switching (TS) in which the receiver periodically switches to decode information and harvest energy, and ii) power splitting (PS) in which the received signal is split into two separate parts with different power to decode information and harvest energy.

However, current interests of SWIPT generally assume that the network nodes are in one-hop [8]–[22] or two-hop [23]–[32] wireless networks.

In one-hop wireless network, SWIPT has been researched for various transmission systems in different contexts [8]–[20] to make tradeoffs between information decoding and energy harvesting in the receiver for better performance, i.e., less transmitting power, higher transmission rate, more received power, or better energy efficiency. While point-to-point single antenna systems (Single Input Single Output, SISO) [5], [8] are focused on at the beginning, most of the recent studies focus on multiantenna systems, i.e., Multiple Input Single Output antenna systems (MISO) [9] or Multiple Input Multiple Output antenna systems (MIMO) [3]. According to the number of receiver, there are two kinds of SWIPT studies, single user [4], [5], [10]–[14] and multiple users [15]–[20]. With the single user, there are only one transmitter and one receiver. The receiver simultaneously obtains information and energy. Later, the studies extend to broadcast and multi-cast applications denoted by multiple users scenario, where multiple receivers obtain information and energy from one common transmitter.

A few works start to consider SWIPT in two-hop wireless network and cooperative networks, where the source transmits data to the destination with the help of a relay node. First, the relay node receives information and harvests energy from the source, and then it exploits the harvested energy to forward information or energy to the destination. Reference [34] considers a amplify-and-forward (AF) relay which minimizes the end-to-end outage probability of information by adjusting the power splitting ratio between information transmission and energy harvesting. References [23]–[29] consider a source and destination pair with one relay. In [30], multiple source and destination pairs share one or several relays. They solve the information and energy allocation problem with the relay nodes.

Reference [33] starts to apply SWIPT to a multi-hop mobile wireless sensor network and shows that compared with no energy harvesting, by SWIPT, the nodes have more remaining energy and the remaining energy among nodes is more balanced. But [33] allocates the information and energy for link after AODV routing selection.

In all above works, the solutions of information and energy allocation are not suitable for multi-hop networks, because the next-hop and past-hop may affect the information and energy allocation while a link is in a path. Further, they don't take the routing selection problem into account. As far as we know, it is the first work that provides a solution to enable SWIPT with routing in multi-hop energy-constrained wireless networks. Our scheme exploits SWIPT technique to significantly increase the network performance of multi-hop energy-constrained wireless networks.

III. SYSTEM MODEL AND SOLUTION OVERVIEW

In this section, we first present our network models and transmission mode , and then introduce a motivation example to illuminate our problem. Finally, we give an overview of our solution.

A. NETWORK MODELS

This paper considers a multi-hop energy-constrained wireless network consisting of N nodes supported by battery, as shown in Fig. 1. Each node is equipped with a single antenna. The data flow may traverse multiple hops in the network. There is one flow, denoted by $F(S \rightarrow D)$ which goes from source node S to destination node D. There are two different transmission modes between any two nodes in the network considered, information transmission (IT) and simultaneous wireless information and power transfer (SWIPT).

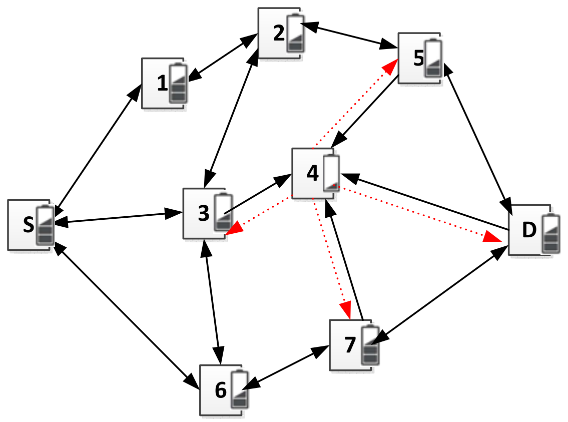


FIGURE 1. Network model.

When the battery is full, the residual energy of node is the battery capacity, denoted by Er_{full}. The residual energy of node i is denoted by Er_i. When the residual energy of node is lower than the minimum energy requirement for forwarding, denoted by Er_{min}, the node will refuse to forward data for other nodes in order to prolong its own life time, which is an inactive node. For example, the residual energy of node 4 is lower than Er_{min}. The node 4 is an inactive node and the link l_{43}, l_{45}, l_{47}, and l_{4D} are inactive. A node is an active node only when its residual energy is higher than Er_{min}.

Benefiting from the SWIPT, the energy harvested by the node 4 from the other node (node 3 as an example) can be as a energy compensation for data forwarding to node 5, 7 and D. It conducts a SWIPT link l_{34}. The node 4 and the links l_{43}, l_{45}, l_{47}, and l_{4D} become active again.

In multi-hop energy-constrained wireless networks with SWIPT, a routing path could be a combination of SWIPT links and IT links, named by SWIPT routing path. For example, as shown in Fig. 4(b), the path of flow is $F(S \rightarrow D) = S \xrightarrow{IT} 3 \xrightarrow{SWIPT:0.3} 4 \xrightarrow{IT} D$, where the second hop link l_{34}^{SWIPT} adopts the SWIPT mode, while the first hop link l_{S3}^{IT} and the third hop link l_{S3}^{IT} adopt the IT mode. We use the superscripts '*SWITP*' and '*IT*' to mark the links' transmission mode.

B. TRANSMISSION MODES

1) INFORMATION TRANSMISSION MODE

IT is widely employed in current wireless networks. A sender node transmits its signal to a receiver node. In the receiver node, the RF signal is all fed into the signal processing circuit to decode information, denoted by information decoder (ID) circuit with blue rectangle in Fig. 2.

In the sender node, the sent baseband signal is denoted by $x(t)$ which is assumed to be a narrow-band signal with power

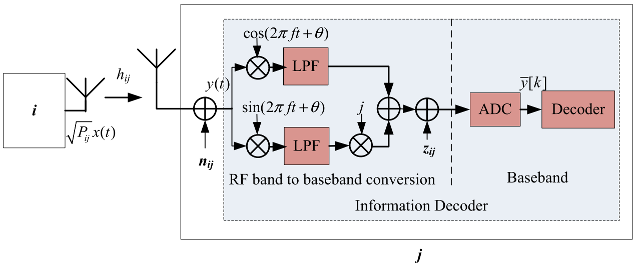


FIGURE 2. Information transmission (IT).

P_{ij} and $E[|x(t)|^2] = 1$. The wireless channel from sender i to receiver j is with channel gain coefficient h_{ij} which captures the effects of path-loss, shadowing, and fading within the channel. The channel power gain is denoted by $|h_{ij}|^2$. All the notations and their definitions in this work are listed in Table 1.

TABLE 1. List of notations.

Notation	Definition
Er_{full}	Battery capacity
Er_i	Residual energy of node i
Er_{min}	Minimum energy requirement for forwarding
P_{ij}	Transmission power from node i to node j
$\|h_{ij}\|^2$	Propagation power gain from node i to node j
σ_{ij}^2	Power of antenna noise from node i to node j
η_{ij}^2	Power of signal conversion noise from node i to node j
γ_{ij}^{IT}	Signal-to-noise rate for IT
γ_{ij}^{SWIPT}	Signal-to-noise rate for SWIPT
ρ_{ij}	Power fraction for decoding information from node i to node j
$1-\rho_{ij}$	Power fraction for harvesting energy from node i to node j
E_{ij}^{eh}	Energy harvesting power from node i to node j
ε	Energy converting coefficient of EH circuit
R_{min}	Minimum SNR requirement
Pc_j	Minimum energy harvesting power requirement for forwarding by node j
P_{max}	Maximum transmission power
α	Path-loss exponent
br	Barriers rate

The received RF signal at the receiver j is denoted by $y(t)$:

$$y(t) = \sqrt{P_{ij}}h_{ij}x(t) + n_{ij}(t), \tag{1}$$

where n_{ij} is the antenna noise and $n_{ij} \sim \mathcal{CN}(0, \sigma_{ij}^2)$.

The circuit of information decoder [5] is shown in Fig. 2. The first part of the circuits is an conversion from the received RF band signal $y(t)$ to a complex baseband signal, which introduces an noise denoted by z_{ij} with $z_{ij} \sim \mathcal{CN}(0, \eta_{ij}^2)$. Then, an analog-to-digital converter (ADC) samples and digitalizes the complex baseband signal to decode information. Assume that the ADC is ideal and with zero noise. The digitalized information is represented by

$$\bar{y}[k] = \sqrt{P_{ij}}h_{ij}x[k] + n_{ij}[k] + z_{ij}[k], \tag{2}$$

where $k = 1, 2, \ldots,$ denotes the symbol index. The signal-to-noise ratio (SNR) of IT is given by

$$\gamma_{ij}^{IT} = |h_{ij}|^2 P_{ij}/(\sigma_{ij}^2 + \eta_{ij}^2). \tag{3}$$

We consider decode-and-forward (DF) networks which are most-frequently used in practice. With DF relaying protocol, only when the SNR is higher than the minimum SNR requirement, does the node successfully decode information and forward it to other nodes.

2) SIMULTANEOUS WIRELESS INFORMATION AND POWER TRANSFER MODE

In this paper, we consider the power splitting (PS) mode of SWIPT receiver architecture [4]. In the power splitting mode, the receiver consists of two circuits, energy harvester (EH) circuit and ID circuit. The received signal is splitted into two parts with different power separately. One part is fed into ID circuit, while the other part is fed into EH circuit, as shown in Fig. 3.

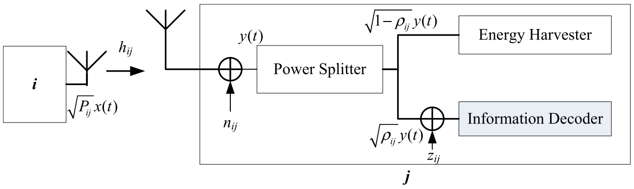


FIGURE 3. Simultaneous wireless information and power transfer (SWIPT).

In SWIPT, the transmitted signal $x(t)$ from the sender i, the wireless channel and the received RF signal $y(t)$ at the receiver j are all same as that in IT.

According to a power splitting ratio $\rho_{ij} \in [0, 1]$, the receiver j splits the received RF signal $y(t)$ with different power by a power splitter [4]. ρ_{ij} is the fraction of power for decoding information and $1-\rho_{ij}$ is that for harvesting energy. After splitting, the part used for the EH circuit is denoted by $y^{EH}(t)$ which can be expressed as

$$\begin{aligned} y^{EH}(t) &= \sqrt{1-\rho_{ij}}y(t) \\ &= \sqrt{(1-\rho_{ij})}(\sqrt{P_{ij}}h_{ij}x(t) + n_{ij}(t)). \end{aligned} \tag{4}$$

According to [5], the energy harvested power at the receiver is

$$E_{ij}^{eh} = \varepsilon(1-\rho_{ij})(|h_{ij}|^2 P_{ij} + \sigma_{ij}^2), \tag{5}$$

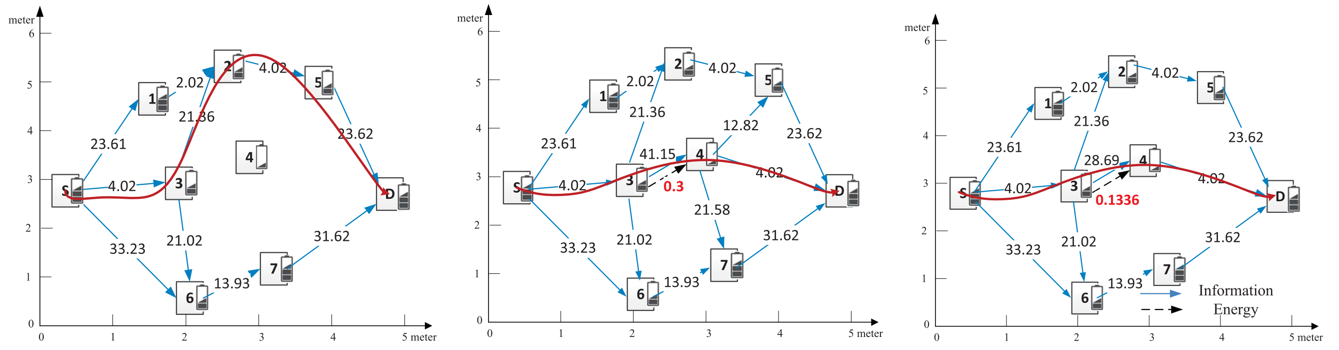
where $\varepsilon \in [0, 1]$ is the energy converting coefficient of EH circuit.

At the same time, the other part is fed into the signal processing or ID circuit and denoted by $y^{ID}(t)$ which can be expressed as

$$\begin{aligned} y^{ID}(t) &= \sqrt{\rho_{ij}}y(t) + z_{ij}(t) \\ &= \sqrt{\rho_{ij}}(\sqrt{P_{ij}}h_{ij}x(t) + n_{ij}(t)) + z_{ij}(t), \end{aligned} \tag{6}$$

where $z_{ij}(t)$ is the RF band to baseband conversion noise and same as that in IT. Therefore, the signal-to-noise ratio of SWIPT is given by

$$\gamma_{ij}^{SWIPT} = \rho_{ij}|h_{ij}|^2 P_{ij}/(\sigma_{ij}^2 + \eta_{ij}^2). \tag{7}$$



(a) (b) (c)

FIGURE 4. **Motivation example. (a) IT. (b) SWIPT. (c) SWIPT after information and energy allocation.**

C. MOTIVATION EXAMPLE

With the aim of providing a effective solution in multi-hop energy-constrained wireless networks with SWIPT, this paper solves the problem of joint routing, information and energy allocation so that the aggregate energy cost of flow is minimized. To illuminate our problem in essence, we take a motivation example to show that only IT or SWIPT without information and energy allocation cannot achieve the good performance in multi-hop energy-constrained wireless networks.

Given the transmission power, if more power is fed into EH circuit, the transmission range is smaller, the neighbor nodes are less, and the nodes with lower residual energy can be charged and act as forwarder nodes. Oppositely, if more power is fed into ID circuit, the transmission range is bigger and the neighbor nodes are more, the nodes with lower residual energy cannot act as forwarder nodes.

Fig. 4 is a multi-hop energy-constrained wireless network consisting of 9 nodes. The battery icon's bar chart in node denotes the residual energy of node. For simplicity, we assume that the SNR and energy harvested power of each link can be obtained by (3) or (5) and (7) depending on the transmission mode. The parameters are same as the simulation setting in Section VI-A.

Initially, nodes communicate with each other only via IT. The flow $F(S \rightarrow D)$ can be end-to-end transmitted through one of four available routing paths, such as $Path_1 = S \xrightarrow{IT} 1 \xrightarrow{IT} 2 \xrightarrow{IT} 5 \xrightarrow{IT} D$, $Path_2 = S \xrightarrow{IT} 3 \xrightarrow{IT} 2 \xrightarrow{IT} 5 \xrightarrow{IT} D$, $Path_3 = S \xrightarrow{IT} 3 \xrightarrow{IT} 6 \xrightarrow{IT} 7 \xrightarrow{IT} D$, and $Path_4 = S \xrightarrow{IT} 6 \xrightarrow{IT} 7 \xrightarrow{IT} D$, as shown in Fig. 4(a). According to (3), to let the node successfully decode and forward information, we can get the minimum transmission power which are considered as the energy cost of transmission. The energy cost of links in these four paths can be obtained: $P_{s1} = 23.61$uW, $P_{s3} = 4.02$uW, $P_{s6} = 33.23$uW, $P_{12} = 2.02$uW, $P_{25} = 4.02$uW, $P_{32} = 21.36$uW, $P_{36} = 21.02$uW, $P_{5D} = 23.62$uW, $P_{67} = 13.93$uW, and $P_{7D} = 31.62$uW. The energy cost of four paths are $P_{Path_1} = P_{s1} + P_{12} + P_{25} + P_{5D} = 53.27$uW, $P_{Path_2} = P_{s3} + P_{32} + P_{25} + P_{5D} = 53.02$uW, $P_{Path_3} = P_{s3} + P_{36} + P_{67} + P_{7D} = 70.59$uW, and $P_{Path_4} = P_{s6} + P_{67} + P_{7D} = 78.78$uW, respectively. The minimum energy cost path $Path_2$ is considered as the final path and the energy cost of flow $F(S \rightarrow D)$ is 53.02uW.

In Fig. 4(b), the node can harvest energy from other nodes via SWIPT to increase its residual energy. Benefiting from the SWIPT, the node 4 can be charged from the node 3, and the link l_{43}, l_{45}, l_{47}, and l_{4D} become active again. The number of available routing paths increases. Except the above four paths, there are three SWIPT routing paths, such as $Path_5 = S \xrightarrow{IT} 3 \xrightarrow{SWIPT:0.3} 4 \xrightarrow{IT} D$, $Path_6 = S \xrightarrow{IT} 3 \xrightarrow{SWIPT:0.3} 4 \xrightarrow{IT} 5 \xrightarrow{IT} D$, and $Path_7 = S \xrightarrow{IT} 3 \xrightarrow{SWIPT:0.3} 4 \xrightarrow{IT} 7 \xrightarrow{IT} D$. The splitting ratio ρ of link l_{34}^{SWIPT} is 0.3. The energy cost of links in these three paths are $P_{34} = 41.15$uW, $P_{4D} = 4.02$uW, $P_{45} = 12.82$uW, and $P_{47} = 21.58$uW, respectively. The energy cost of these three paths are $P_{Path_5} = P_{s3} + P_{34} + P_{4D} = 49.19$uW, $P_{Path_6} = P_{s3} + P_{34} + P_{45} + P_{5D} = 69.17$uW, and $P_{Path_7} = P_{s3} + P_{34} + P_{47} + P_{7D} = 85.69$uW, respectively. Therefore, the minimum energy cost path of flow $F(S \rightarrow D)$ is $Path_5$ with 49.19uW. The energy cost decreases about 8.3 percent compared with that in Fig. 4(a).

With the above-selected routes, we apply allocation to improve the network performance. In Fig. 4(c), we change the split ratio ρ of link l_{34}^{SWIPT} to 0.1336. The energy cost of link l_{34}^{SWIPT} reduces to 28.69uW, at the same time the forwarder node 4 can successfully decode information. The energy cost of $Path_5$ reduces to 36.72uW. The energy cost decreases about 25.3 percent compared with that in Fig. 4(b).

The above example demonstrates that SWIPT can improve the performance of multi-hop energy-constrained wireless networks, but considering only routing or information and energy allocation is not enough for achieving the maximum performance. Transmission mode chosen, information and energy allocation interact with routing selection, and we should simultaneously consider all three aspects.

D. SOLUTION OVERVIEW

To solve the problem, inspired by the energy allocation in cooperative routing [35]–[37], we propose a solution framework which is formed with two important components: information and energy allocation, and SWIPT routing.

First, the next-hop and past-hop may affect the information and energy allocation of link because all links are in paths in multi-hop energy-constrained wireless networks. We introduce a novel allocation model to formulate the link information and energy allocation problem with forwarding in a path, which is dependent on the next-hop node. After a node j is selected as the next-hop node, the next-hop node should successfully decode the information and the energy harvested power can support it to further forward the information to the destination. Under the two conditions, the sender node can calculate the split ratio and transmission power to minimize energy cost. We design an iterative allocation algorithm to solve it.

Second, in order to select the next-hop nodes and path, based on the allocation model, we proposes a novel routing metric and a routing algorithm. Every node periodically calculates the routing metric of energy cost (Ecost). Ecost can evaluate the energy consumption of link transmitted with IT or SWIPT and choose a transmission mode for link. Based on this metric, when finding path for flow, an energy-aware routing algorithm is run to find the SWIPT routing path and the split ratio of links along the path. By the metric, the transmission mode selection be easily incorporated into path finding.

In following sections, we introduce the detailed algorithms for each part.

IV. INFORMATION AND ENERGY ALLOCATION

As shown in the motivation example of Section III-C, the information and energy allocation can reduce energy consumption and thus improve the transmission performance. The main function of information and energy allocation is to decide the value of transmission power, how many percent of power for information decoding and how many percent of power for energy harvesting in the total received power.

A. ALLOCATION PROBLEM FOR FORWARDING

For practical implementation of the information and energy allocation in a multi-hop energy-constrained wireless network, we need to follow two basic constrains: (1) the information after splitting should be successfully decoded, (2) the receiver node is able to and willing to further forward information to the destination.

For end-to-end communication with DF protocol, the receiver node should firstly decode information and then forward information to the next-hop node. Therefore, the information should be successfully decoded in the receiver node. According to the DF protocol, the SNR of received information should be no lower than the minimum SNR requirement denoted by R_{min}, while successful decoding, formulated by (8).

$$\gamma_{ij}^{SWIPT} = \rho_{ij}|h_{ij}|^2 P_{ij}/(\sigma_{ij}^2 + \eta_{ij}^2) \geq R_{min} \tag{8}$$

After successfully decoding, the receiver node needs to be able to and willing to further forward information to the destination because data forwarding consumes its energy. The receiver node can exploit the harvest energy from past-hop node as the energy compensation for forwarding information to its next-hop node. For avoiding the decrease of the receiver node's residual energy, the energy harvesting power E_{ij}^{eh} of receiver node should be larger than the receiver node's energy harvesting power requirement for forwarding to the next-hop node, denoted by Pc_j. Therefore, when the forwarding behavior doesn't reduce the residual energy, the receiver node is willing to forward, formulated by (9).

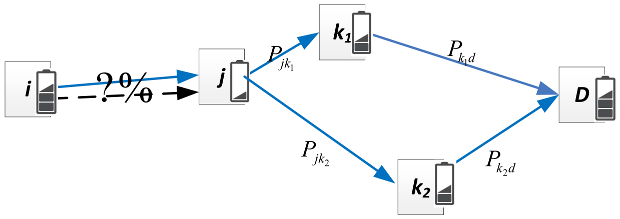


FIGURE 5. Energy harvesting power requirement depending on its next-hop node.

$$E_{ij}^{eh} = \varepsilon(1-\rho_{ij})(|h_{ij}|^2 P_{ij} + \sigma_{ij}^2) \geq Pc_j \tag{9}$$

It is noted that node j may have different values of energy harvesting power requirement for forwarding which depend on its next-hop node. Because different next-hop nodes have different distances and channels, such as node k_1 and node k_2, the transmission powers from node j to its next-hop nodes are P_{jk_1} and P_{jk_2}, respectively, which lead to different energy consumptions for forwarding, as shown in Fig. 5. For different energy consumptions the energy harvesting requirements must be different. Therefore, after choosing different nodes as the next-hop, the values of energy harvesting power requirement for forwarding Pc_j are different.

Further, for the link l_{ij}, only the next-hop node of node j is known, the energy harvesting power requirement for forwarding Pc_j is able to be obtained. For clarity, in our allocation problem, we assume that the next-hop node of node j has been selected by the SWIPT routing algorithm introduced later in next section and Pc_j is known. In next section, we describe how to set the energy harvesting power requirement for forwarding according to the next-hop node.

The transmission power is no larger than the maximum transmission power P_{max}. The splitting ratio ρ is in the range of 0 to 1. The allocation objective is to minimize the energy consumption which can be considered as transmission power. Therefore, according to (8) (9), we can describe the information and energy allocation problem for forwarding as follow:

$$\begin{aligned} &\min_{\rho_{ij}, P_{ij}} P_{ij} \\ &s.t.\ \gamma_{ij}^{SWIPT} = \rho_{ij}|h_{ij}|^2 P_{ij}/(\sigma_{ij}^2 + \eta_{ij}^2) \geq R_{min} \\ &\quad E_{ij}^{eh} = \varepsilon(1-\rho_{ij})(|h_{ij}|^2 P_{ij} + \sigma_{ij}^2) \geq Pc_j \\ &\quad P_{ij} \in [0, P_{max}] \\ &\quad \rho_{ij} \in [0, 1], \end{aligned} \tag{10}$$

where the variables are ρ_{ij}, P_{ij}.

B. ALLOCATION ALGORITHM

In this subsection, we exploit the lagrange multiplier algorithm to solve the problem (10). By introducing lagrange multipliers a, b, we have the augmented lagrange function of the problem (10):

$$\begin{aligned} &L(\rho_{ij}, P_{ij}, a, b, \mu) \\ &\quad = P_{ij} + \frac{1}{2\mu}(\min\{0, \mu(E^{eh}_{ij} - Pc_j) - a\}^2 - a^2) \\ &\qquad + \frac{1}{2\mu}(\min\{0, \mu(\gamma^{SWIPT}_{ij} - R_{min}) - b\}^2 - b^2). \end{aligned} \tag{11}$$

Inspired by the PHR algorithm proposed by Rockfellar [38], an iterative information and energy allocation algorithm (IEA) of the problem can be described, as shown in algorithm 1.

Algorithm 1 Information and Energy Allocation Algorithm

```
Input: $i, j, R_{min}, P_{max}, Pc_j, |h_{ij}|^2, \sigma^2_{ij}, \eta^2_{ij}$
Output: $\rho_{ij}, P_{ij}$
1: Initialization. Set $\rho^0_{ij}, P^0_{ij}, a^1, b^1 \in \mathbb{R}, \mu > 0, 0 \le \phi \ll 1, \upsilon \in (0,1), \eta > 1, k \leftarrow 1$.
2: Solve the problem (12). Based on the $\rho^{k-1}_{ij}, P^{k-1}_{ij}$, solve the no-constrained problem
     $\min_{\rho_{ij}, P_{ij}} L(\rho_{ij}, P_{ij}, a, b, \mu)$
     $= P_{ij} + \frac{1}{2\mu}(\min\{0, \mu(E^{eh}_{ij} - Pc_j) - a\}^2 - a^2)$
     $+ \frac{1}{2\mu}(\min\{0, \mu(\gamma_{ij} - R_{min}) - b\}^2 - b^2)$   (12)
   to get the $\rho^k_{ij}, P^k_{ij}$.
3: Check the stop criterion, if $\beta^k \le \phi$, stop the loop and return $\rho^k_{ij}, P^k_{ij}$; otherwise, goto step 4.
     $\beta^k = (\min\{(Pc_j - \varepsilon(1 - \rho^k_{ij})(|h_{ij}|^2 P^k_{ij} + \sigma^2_{ij})), \frac{a^k}{\mu}\}^2$
     $+ \min\{(R_{min} - \rho^k_{ij}|h_{ij}|^2 P^k_{ij}/(\sigma^2_{ij} + \eta^2_{ij})), \frac{b^k}{\mu}\}^2)^{1/2}$   (13)
4: Update $\mu$, if $\beta^k \ge \upsilon\beta^k, \mu := \eta\mu$.
5: Update the lagrange multiplier $a, b$, according to
     $a^{k+1} = \max\{0, a^k + \mu(Pc_j - \varepsilon(1 - \rho^k_{ij})(|h_{ij}|^2 P^k_{ij} + \sigma^2_{ij}))\}$
     $b^{k+1} = \max\{0, b^k + \mu(R_{min} - \rho^k_{ij}|h_{ij}|^2 P^k_{ij}/(\sigma^2_{ij} + \eta^2_{ij}))\}$   (14)
6: $k \leftarrow k + 1$, goto step 2.
```

In initialization, the initial parameters are random set. In the each k-th iteration, node j locally solves the non-constrained problem (12) to get splitting ratio and transmission power. Then, the stop criterion is checked whether it has converged to stop the loop. If not, the penalty parameter μ is updated, and the lagrange multipliers a^{k+1}, b^{k+1} are updated by (14) according to splitting ratio and transmission power in the k-th iteration.

V. ENERGY-AWARE SWIPT ROUTING

To quantify the energy consumption of a link and a path in multi-hop energy-constrained wireless networks, in this section, we first introduce a novel routing metric, named by energy cost (Ecost). Based on the metric, we propose an energy-aware routing algorithm to better exploit the benefit of SWIPT for a higher transmission performance.

A. ROUTING METRIC

In multi-hop energy-constrained wireless networks, there are two transmission modes (IT and SWIPT). If the node i transmits data to the node j with IT, we define that the energy cost of link l^{IT}_{ij}, denoted by $Ecost(i,j)^{IT}$, is equal to the transmission power P_{ij}. In addition, for successful decoding, the SNR should be no lower than the minimum SNR requirement R_{min}:

$$Ecost(i,j)^{IT} = P_{ij}, \tag{15}$$

$$\gamma^{IT}_{ij} \ge R_{min}. \tag{16}$$

Therefore, the minimum energy cost of link l^{IT}_{ij} can be calculated by using (17):

$$Ecost(i,j)^{IT} \ge (\sigma^2_{ij} + \eta^2_{ij})R_{min}/|h_{ij}|^2. \tag{17}$$

If the node i transmits data to the node j with SWIPT, a part of power from node i is transformed to energy in the node j, which is not consumed in the transmission. We should subtract this part. Therefore, the energy cost $Ecost(i,j)^{SWIPT}$ of the link l^{SWIPT}_{ij} is equal to the transmission power deducted by the energy harvesting power of node j, calculated by (18):

$$Ecost(i,j)^{SWIPT} = P_{ij} - E^{eh}_{ij}. \tag{18}$$

The routing metric of link is defined as the minimum energy cost between IT and SWIPT transmission modes:

$$Ecost(i,j) = \min\{Ecost(i,j)^{SWIPT}, Ecost(i,j)^{IT}\}. \tag{19}$$

When the all signal is fed into ID circuit, that is, the splitting ratio is 1, the energy harvesting power should be zero, which is same as IT. Therefore, the metric can be reformulated by (20). Based on the metric, the node can decide to take IT or SWIPT mode via the splitting ratio. While the splitting ratio is 1, it takes IT mode. While the splitting ratio is not 1, it takes SWIPT mode.

$$Ecost(i,j) = P_{ij} - (1 - \rho_{ij})E^{eh}_{ij} \tag{20}$$

The routing metric of a path $path_{sd}$ is the sum of all links' metric in the path:

$$Ecost(s,d) = \sum_{l_{ij} \in path_{sd}} Ecost(i,j). \tag{21}$$

We define a binary variable r_{ij}, which has value 1 if the link l_{ij} is active in the path of flow $F(S \rightarrow D)$, and value 0 otherwise. Considering that flow conservation holds for each node to select path, we must have

$$\sum_j r_{ij} - \sum_j r_{ji} = \begin{cases} 1, & i = s \\ -1, & i = d \\ 0, & other. \end{cases} \tag{22}$$

If node i is selected as the next-hop node of node j, that is, link l_{ji} is active. The transmission power from node j to its next-hop node i is the power cost for forwarding by node j. Therefore, we define the energy harvesting power requirement for forwarding Pc_j as the transmission power from node j to its next-hop node i:

$$Pc_j = P_{ji}, \quad \text{if } r_{ji} = 1. \tag{23}$$

Our objective is to find a path with the minimum energy cost. Then, according to (8)(9)(22)(23), the combined problem of routing, information and energy allocation, and transmission mode chosen can be formulated as problem (24).

$$\begin{aligned} \min_{\boldsymbol{\rho},\mathbf{P},\mathbf{r}} \; & \sum_{l_{ij}} r_{ij}(P_{ij} - (1-\rho_{ij})E_{ij}^{eh}) \\ s.t.\; & \gamma_{ij}^{SWIPT} = \rho_{ij}|h_{ij}|^2 P_{ij}/(\sigma_{ij}^2 + \eta_{ij}^2) \geq R_{min}, \quad \forall i,j \\ & E_{ij}^{eh} = \varepsilon(1-\rho_{ij})(|h_{ij}|^2 P_{ij} + \sigma_{ij}^2) \geq Pc_j, \quad \forall i,j \\ & \sum_j r_{ij} - \sum_j r_{ji} = \begin{cases} 1, & i = s \\ -1, & i = d \\ 0, & other, \end{cases} \quad \forall i \\ & Pc_j = P_{ji}, \quad \text{if } r_{ji} = 1, \quad \forall j \\ & P_{ij} \in [0, P_{max}], \quad \forall i,j \\ & \rho_{ij} \in [0, 1], \quad \forall i,j \\ & r_{ij} \in \{0, 1\}, \quad \forall i,j \\ & i,j \in [1 \ldots N], \end{aligned} \tag{24}$$

where the variables are $\boldsymbol{\rho}$, $\mathbf{P}$, $\mathbf{r}$. It is complex to solve the problem (24) directly, because the the energy harvesting power requirement for forwarding Pc_j is dependent on the route selection. Therefore, we design a SWIPT routing algorithm combined allocation algorithm 1 in next subsection.

B. ENERGY-AWARE SWIPT ROUTING ALGORITHM

In this subsection, for decoupling the resource allocation and route selection, we design an energy-aware SWIPT routing algorithm (ESWIPTR) to implement the receiver node's next-hop node selection before resource allocation for a sender and receiver pair. ESWIPTR is inspired by dijkstra routing with resource allocation [39]–[41], as shown in algorithm 2. The basic idea is that when allocating the information and energy for a sender and receiver pairs, the path from the receiver to destination has been selected and the receiver's next-hop is known. If not, the allocating is delayed. Therefore, starting from destination, the routing algorithm finds the minimum energy cost path to destination for all nodes and allocates the information and energy for the selected link by algorithm 1.

For a graph $G(V, E)$, the minimum energy cost paths from all nodes to a destination d are calculated by the algorithm.

Algorithm 2 The Energy-Aware SWIPT Routing Algorithm

```
Input: $G(V,E), d, R_{min}, P_{max}$
Output: Path from $i$ to $d$, with each hop $(i,j)$ and $\rho_{ij}, P_{ij}$
 1: for each node $i$ in V do
 2:     Ecost$_i \leftarrow \infty$
 3:     $Pc_i \leftarrow \infty$
 4:     $F_i \leftarrow$ NIL
 5: end for
 6: Ecost$_d \leftarrow 0$
 7: $Pc_d \leftarrow 0$
 8: $S \leftarrow \emptyset$
 9: $Q \leftarrow V$
10: while Q $\neq \emptyset$ do
11:     $j \leftarrow$ EXTRACT-MIN(Q)
12:     S $\leftarrow$ S $\bigcup \{j\}$
13:     for each incoming edge $(i,j) \in$ E do
14:         if $Ecost_i > Ecost_j$ then
15:             use algorithm 1 with
                $i, j, R_{min}, P_{max}, Pc_j, |h_{ij}|^2, \sigma_{ij}^2, \eta_{ij}^2$ to get $\rho_{ij}, P_{ij}$
16:             $Ecost_i' \leftarrow P_{ij} - E_{ij}^{eh} + Ecost_j$
17:             if $Ecost_i > Ecost_i'$ then
18:                 $Ecost_i \leftarrow Ecost_i'$
19:                 $F_i \leftarrow j$
20:                 $Pc_i \leftarrow P_{ij}$
21:             end if
22:         end if
23:     end for
24: end while
```

In the algorithm, $Ecost(i, d)$ is replaced simply by $Ecost_i$ for convenience which presents an upper-bound on the metric of the minimum energy cost path from i to d. Furthermore, a corresponding forwarder F_i stores the next forwarder used for i to reach d in the minimum energy cost path. Pc_i stores the energy harvesting power for forwarding from i to F_i. Set S is the set of nodes which already have a minimum energy cost path. A Priority queue Q consists of all nodes $i \in V - S$ which still have not found a minimum energy cost path, which takes the $Ecost_i$ values of nodes as the key.

The $Ecost_i$ is kept by each node as the node metric. At the while loop in line 10, we select the node with the minimum $Ecost$ from Q denoted by j. When node is selected, it gets settled. For each incoming edge $(i, j) \in E$, it is need to check whether the metric $Ecost_i$ is larger than the metric $Ecost_j$ of the node just settled or not. If no, the node i has found the minimum energy cost path before. If yes, we temporarily set j as the forwarder of node i. The next-hop node of node j is F_j and the energy harvesting power for forwarding by node j is Pc_j which have been known because node j have be settled before. Therefore, the ρ_{ij}, P_{ij} can be obtained by algorithm 1. The node temporary metric $Ecost_i'$ can be calculated too. If $Ecost_i$ is larger than the temporary metric $Ecost_i'$, then node j is set as the forwarder F_i, metric $Ecost_i$ is updated accordingly, and the energy harvesting power for forwarding

Pc_i is set to P_{ij}. In the latter round of the while loop, when node i is settled, the forwarding power cost Pc_i is needed for algorithm 1 in line 14, which has obtained before.

C. DISTRIBUTED PROTOCOL FOR ESWIPTR

The above algorithm is centralized. Therefore, a distributed synchronous proactive protocol is presented according to the distributed Bellman-Ford protocol. Each node keeps a routing table which consists of N entries for each destination <destination, Ecost weight, forwarder, forwarding power cost>. We assume that the time line is discrete and one iteration in lines 13-23 of ESWIPTR is processed in every time interval. Initially, all node initial their routing table entry to all destinations. In each time interval, each node exchanges the path vector with all its neighbors by sending tuples <destination, Ecost weight, forwarding power cost>. Then, the node i can run lines 13-23 of ESWIPTR for each neighbor node and update its routing tables by the new path vectors from neighbors, which is path vector updating.

Since the synchronous proactive protocol should be time synchronization, an asynchronous proactive table-driven protocol is proposed. Path vector tuples <destination, Ecost weight, forwarding power cost> are periodically broadcast to all its neighbors. The exchanging and updating operation frequency depend on the network scale and the wake up and sleep states of nodes. Whenever any entry in the routing table is updated, the path vector exchanging is triggered. After the updated path vector is received by a node, the node uses lines 13-23 of ESWIPTR to recalculate its path to the destination. When the recalculating leads to a change in routing table, it will trigger another path vector exchanging in next time interval.

In a dynamic network, our synchronous proactive protocol should periodically exchange and update the path vector all the time. In a static network, this protocol terminates after $|V|$ times iterations. In each iteration, each node exchanges the route table with its neighbors and updates its route metric Ecost according to the neighbors route metrics. In the $k-$th iteration, each node can exchange the route table with k hops neighbors, which can obtain the path to the k hops neighbors. The network consists of $|V|$ nodes and the longest path is $|V|$ hops. Therefore, the distributed synchronous proactive protocol terminates after $|V|$ times of iterations.

VI. SIMULATION RESULTS AND ANALYSIS

In this section, the extensive simulations are carried out to evaluate our algorithms.

A. SIMULATION SETTING

In our simulation, the default simulation setting is as follows. 30 nodes are located randomly in a $50m \times 50m$ field except for the source and the destination. The source and destination node are set at the diagonal corner of the square area, that is, source node is at (0,0) and destination node is at (50,50).

We assume that the full energy of node Er_{full} equals to one energy unit. All nodes' residual energy Er satisfy stochastic distribution from 0 to Er_{full}. The minimum energy requirement for forwarding Er_{min} is set to 0.4. The maximum transmission power P_{max} set to 100mW. The minimum SNR requirement R_{min} is set to 20dB. Following the parameter setting in [29], the channel power gain from node i to node j is modeled by $|h_{ij}|^2 = 1/(1 + ||i-j||^{\alpha})$, where $||i-j||$ is the distance (in meters) between node i and node j, and α is the path-loss exponent. We take account of the urban cellular communication environment [42] and the path-loss exponent α is 2.7. We assume that all nodes have the same noise set of parameters [17], i.e., $\sigma_{ij}^2 = \sigma^2, \eta_{ij}^2 = \eta^2$. Moreover, without loss of generality, we set the power of noises to $\sigma^2 = -50\text{dBm}$, $\eta^2 = -70\text{dBm}$ in all simulations. The energy converting coefficient of EH circuit ε is set to 0.65.

TABLE 2. **Simulation parameters.**

Parameter	Value	Parameter	Value
Er_{full}	1	Er_{min}	0.4
P_{max}	100mW	R_{min}	20dB
$\|h_{ij}\|^2$	$1/(1+\|\|i-j\|\|^{\alpha})$	α	2.7
σ_{ij}^2	-50dBm	η_{ij}^2	-70dBm
ε	0.65	br	30%

A direct link between two nodes may be not available (e.g., coverage extension scenario, physical barriers). Some physical barriers in the network make that two nodes are in each transmission range but can't communicate. The barriers rate br is the percent of unavailable direct link due to barriers, where the default value is set to 30%. All the simulation parameters are listed in Table 2.

There is no existing work studying SWIPT with routing in multi-hop energy-constrained wireless networks. We evaluate the effectiveness of our algorithms for joint routing, information and energy allocation and the benefit of SWIPT in multi-hop networks by comparing the results from two different implementation schemes. We implement SWIPT schemes in a multi-hop network which is our proposed Algorithm 2, denoted by SWIPT. We also implement an additional schemes based on IT without considering SWIPT, denoted by IT, where we use the (17) as the routing metric and apply algorithm 2 to find the path with the minimum energy cost for flow.

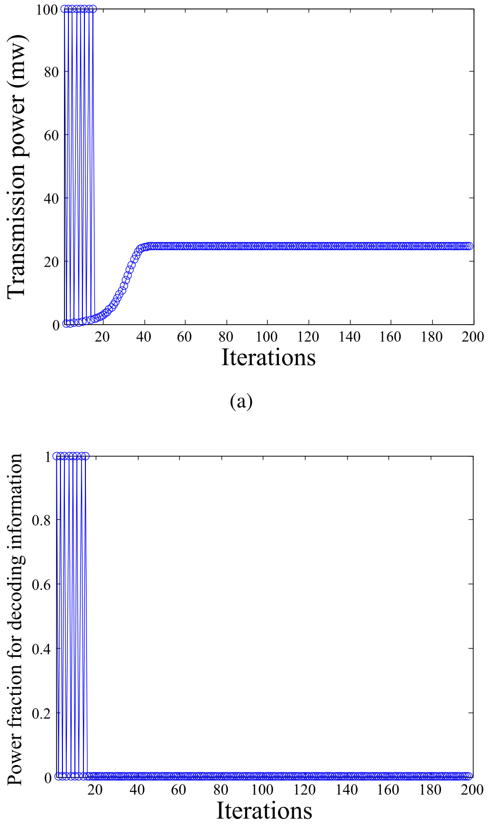
We use two metrics to evaluate the performance. Energy cost is the routing metric from the source to the destination. We also calculate the aggregative energy cost which is the energy cost sum from all other nodes to the destination.

Various factors affect the performance. We perform three set of simulations to analyze the effect of node density, minimum energy requirement for forwarding, and barrier rate. In the next subsection, the simulation results are presented respectively .

B. SIMULATION RESULTS

1) CONVERGENCE

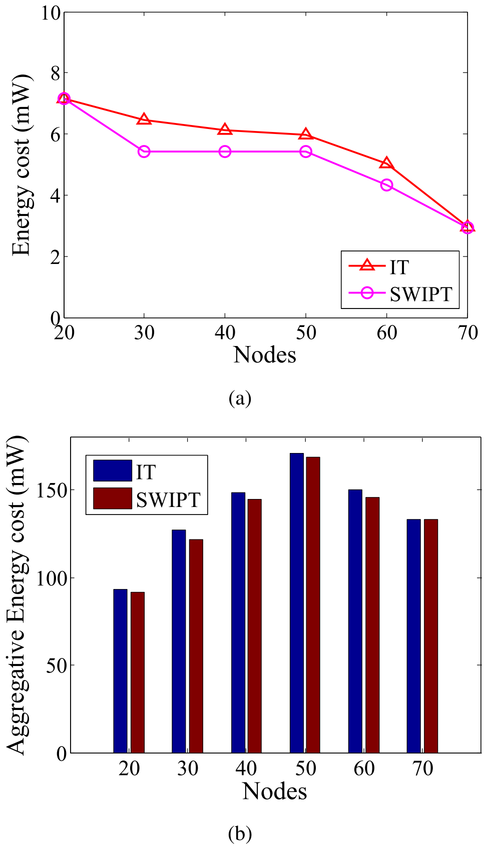
The convergence property of the proposed algorithm is considered. Note that the variables should converge firstly in the algorithm 1 which is the basis of the algorithm 2. For clarity,



(a)

(b)

FIGURE 6. **Convergence property of algorithm 1. (a) Transmission power. (b) Power fraction for decoding information.**



(a)

(b)

FIGURE 7. **Energy results with different node density. (a) Energy cost. (b) Aggregative energy cost.**

we show the convergence of the power variable on the algorithm 1, in which the input variables are $P_{max} = 100\text{mW}$, $Pc_j = 1\text{mW}$, $R_{min} = 10\text{dB}$, $|h_{ij}|^2 = 0.0625$. And the inner variables of algorithm 1 are $\mu = 0.5, \phi = 0.01$, $\upsilon = 0.5, \eta = 1.2$.

The evolution of transmission power and power fraction for decoding information in the algorithm 1 are shown in Fig. 6. Notably, the transmission power and power fraction for decoding information variable fluctuate in the first 40 iterations and reacher equilibrium after 40 iterations. The stable value of transmission power and power fraction for decoding information are 24.61mW and 5^{-5}, respectively. Due to the energy harvesting requirement, all most of the received power is fed into the EH circuit and the power fraction for decoding information is very small.

2) IMPACT OF NODE DENSITY

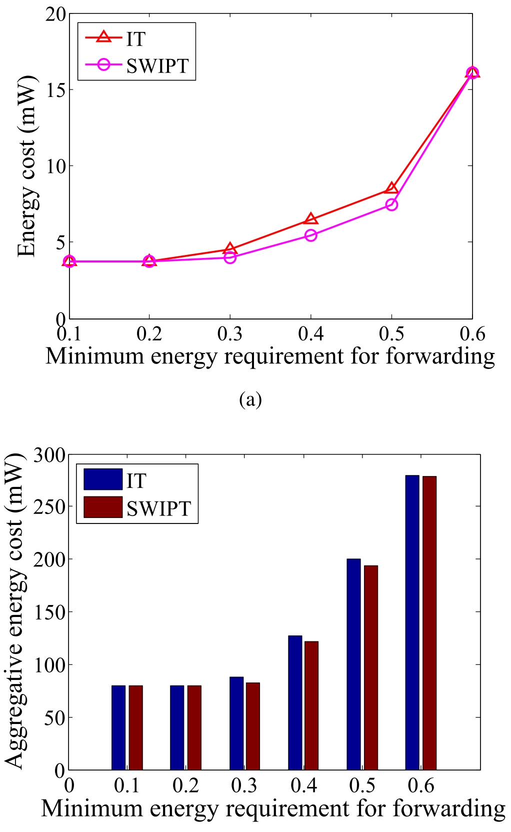
To analyze how the node density impacts the network performance, the number of nodes is varied from 20 to 70 in the network.

The energy cost with two routing schemes all decrease, as shown in Fig. 7(a), because when the number of nodes increases, the resource of forwarder nodes becomes richer. In detail, when the number of nodes increases to 30, the energy cost of SWIPT starts to be lower than that of IT. Because of the increase of inactive forwarder nodes, forwarding packet through the lower energy nodes by SWIPT can be better than through active forwarder nodes by IT. The energy cost gains between SWIPT and IT are in the range of 10% to 19%. When the number of nodes is 70, the energy cost gain between SWIPT and IT is ignored. The reason is that there are dense active forwarder nodes. The node can find better forwarder nodes and path without SWIPT.

As shown in Fig. 7(b), as the increase of the number of nodes, the aggregative energy cost experiences two periods. First, due to the increase of number of nodes, the aggregative energy cost also increases because it is the sum of all nodes' energy cost. Second, due to the increase of active forwarder nodes, each node's energy cost decreases significantly. Although the number of nodes increase, the aggregative energy cost decreases. From the aspect of all nodes, 10% to 23% nodes can decrease its energy cost by SWIPT. Therefore, the SWIPT is more suitable for medium node density.

3) IMPACT OF MINIMUM ENERGY REQUIREMENT FOR FORWARDING

To investigate how the number of inactive nodes whose residual energy is lower than Er_{min} impacts the network



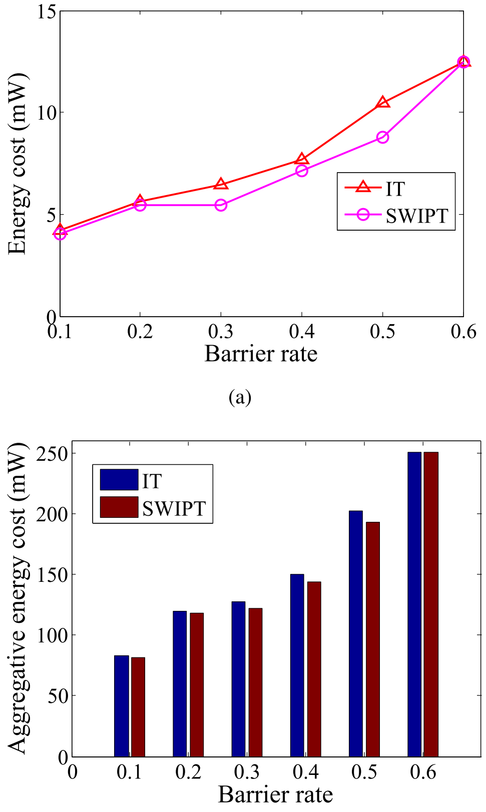
(a)

(b)

FIGURE 8. **Energy results with different minimum energy requirement for forwarding. (a) Energy cost. (b) Aggregative energy cost.**

performance, we vary the minimum energy requirement for forwarding from 0.1 to 0.6 in the network while setting the number of nodes to 30. The higher minimum energy requirement for forwarding means more inactive nodes and less active nodes, while lower minimum energy requirement for forwarding means less inactive nodes and more active nodes.

As shown in Fig. 8(a), as the minimum energy requirement for forwarding increases, the energy cost increases as expected due to the decrease of active forwarder nodes for end-to-end communication. When the minimum energy requirement for forwarding is smaller than 0.2, the active forwarder nodes are sufficiency and the source can find better forwarder nodes by IT. When the the minimum energy requirement for forwarding becomes higher, the active forwarder nodes decrease. Therefore, SWIPT can exploit the lower energy nodes or inactive nodes with lower energy cost and have better performance. The energy cost gains between SWIPT and IT are in the range of 13% to 19%. However, when the minimum energy requirement for forwarding is up to 0.6, because most of nodes refuse to forward packet, the energy costs of IT and SWIPT are almost same. The aggregative energy cost follows the same rule of energy cost, as shown in Fig. 8(b).



(a)

(b)

FIGURE 9. **Energy results with different barrier rate. (a) Energy cost. (b) Aggregative energy cost.**

4) IMPACT OF BARRIER

To investigate how the barrier impacts the network performance, we vary the barrier rate *br* from 10% to 60% in the network while setting other parameters to the default values.

As shown in Fig. 9(a)(b), as the barrier rate increases, the energy cost and aggregative energy cost increase as expected due to the decrease of direct links. When the barrier rate is smaller than 10%, the direct links are sufficiency and the hops of end-to-end communication are fewer. The energy costs of IT and SWIPT are same. When the barrier rate becomes higher, the direct links decrease and nodes need more hops and forwarding for end-to-end communication. Therefore, SWIPT has better energy performance than IT. The energy cost gains between SWIPT and IT are in the range of 3% to 19%. When the barrier rate is 60%, the links between node and the inactive node also reduce because there are too less SWIPT links in the network. Therefore, SWIPT obtains the same performance, comparing with IT. Therefore, the SWIPT is more suitable for medium node density, minimum energy requirement for forwarding, and barrier.

VII. CONCLUSION

To reach the full potential of SWIPT in multi-hop energy-constrained wireless networks, a joint solution is proposed, in which energy-aware routing at the network layer, transmission mode choosing at the MAC layer, and information and energy allocation at the physical layer can work coherently together to minimize the network energy consuming. We introduce the constraints of forwarding and formulate the information and energy allocation which is solved by an efficient iterative algorithm. The transmission mode choosing problem is combined into the routing selection with the novel metric. The energy-aware SWIPT routing algorithm allocates the information and energy of link during path finding process. Our solution is the first work to effectively exploit SWIPT and routing technique for improving the performance of multi-hop energy-constrained wireless networks. The analytical results are obtained by extensive simulations, which demonstrate that the proposed solution is effective and incorporating SWIPT in multi-hop networks can achieve the significant energy cost gains, with well designed algorithms for joint routing, transmission mode choosing, and information and energy allocation, compared with information transmission.

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