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# Energy enhancement and efficient route selection mechanism using H-SWIPT for multi-hop IoT networks

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**Abstract:** Simultaneous wireless information and power transfer (SWIPT) is recently emerging as one of the vital solutions to prolong the lifetime of energy constrained wireless sensor nodes. However, current works on SWIPT considered only the immediate past-hop node's RF signal as a source of energy harvesting in multi-hop Internet of things (IoT) networks. In case of weak radio frequency (RF) signal, the amount of harvested energy does not support for continuous communication. Hence, in this paper a new energy harvesting mechanism is proposed which considers multiple sources (MS) such as (1) sink broadcasting energy, (2) co-channel interference, (3) neighbor nodes' RF signal, and (4) immediate past-hop node's RF signal for energy harvesting. Towards such prospect, a new SWIPT architecture is proposed called hybrid SWIPT (H-SWIPT) by integrating time switching (TS) and power splitting (PS) architectures. Furthermore, an efficient route selection mechanism is introduced to minimize the total energy consumption of the path based on an energy cost metric. To validate the proposed mechanism, simulation experiments are conducted and obtained the superiority of H-SWIPT compared with existing methods in terms of average harvested energy. Further, the effectiveness of proposed method performance is investigated through energy cost at different node density and barrier rates.

**Key words:** simultaneous wireless information and power tansfer (SWIPT); power splitting; time switching; energy consumption; co-channel interference; Internet of things (IoT)

## 1 Introduction

Internet of things (IoT) has generated countless possibilities among heterogeneous devices within a network[1]. In the era of IoT, by 2025 there will be 75.44 billion communication devices (e.g., sensors) that are going to be connected wirelessly through the internet[2, 3]. Most of the time, these devices are located in an extremely resource-constrained environment. Specifically, small sensors will be integrated invisibly into the human body, vehicles, clothing, and walls and they are hard to access for manual recharging or wired connection.

It gives rise to the necessity to improve the network lifetime and capability of the sensors concerning energy consumption. Furthermore, sensors have inadequate energy sources and they mostly operate on batteries with a specific energy capability and their repeated replacement can increase the cost or sometimes it is impossible. It creates an extreme performance obstruction for reliable wireless communication networks like IoT. A better way to increase the lifespan of conventional wireless communication networks is to let them harvest energy itself either from external sources or from the environment[4, 5]. To generate electricity, few renewable energy sources from the environment like solar, wind, and geothermal are available but they are dependent on climate and location. Moreover, they are not available for indoor/enclosed environments, which may produce a problem for mobile nodes. The most

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challenging task in any wireless communication system is to provide a stable and uninterrupted quality of service but it is not possible because of the uncontrollable nature of natural energy sources by making the use of energy harvesting (EH).

The viable solution for the above problem is to transfer the power wirelessly or simultaneous wireless information and power transfer (SWIPT)[6–9]. SWIPT serves as a basic building block for self-sustained communication networks and the key to unlock the capability of IoT networks. Energy harvesting in SWIPT is one of the major concentrated areas for researchers to improve the IoT network lifetime. SWIPT consists of two basic receiver architectures: time switching (TS) and power splitting (PS) architectures. Both receiver architectures consist of a single antenna which is used for information decoding (ID) and EH. In TS, one time slot is used for EH and the next time slot is used for ID[10]. In PS architecture, the radio frequency (RF) signal received by the receiver node is divided into two parts based on splitting ratio: one is for ID and the other is for EH. Most of the researchers have used either PS or TS protocol to improve the network performance. However, they considered past-hop node' s RF signal only as a source to harvest the energy at the receiver node. Moreover, the quantity of harvested energy is not enough to decode and forward the data successfully to the next-hop node or destination due to the following reasons: continuous sensing, computation, and data transmissions of each sensor/device in the network, presence of different channels or radio mediums between the sensors/devices, and uneven distances between the sensors/devices. So, there is a need to improve the energy harvesting capacity of each node in the network.

Towards such an aim, in this paper we propose a new energy harvesting SWIPT architecture called as hybrid SWIPT architecture with multiple sources (H-SWIPT-MS) followed by an energy efficient path selection mechanism. Under this architecture, we propose to integrate TS with PS architectures and formulate a new hybrid architecture called H-SWIPT. Under the harvesting mechanism, we propose to consider multiple sources (e.g., sink, neighbor node, and co-channel interference) for energy harvesting, instead of single source like conventional SWIPT. Further, towards the path selection, we propose an energy cost aware routing algorithm which minimizes the energy consumption. The major contributions of this work are summarized below.

(1) To improve the lifetime of an IoT network, this work introduces a new architecture called hybrid SWIPT (H-SWIPT) that considers PS and TS protocols simultaneously. In this architecture, by adjusting the TS and PS ratios, the hybrid protocol allows a lot of flexibility in how much power is spent on EH and ID.

(2) To increase the energy harvesting capacity of an IoT network, this work proposes a new harvesting strategy based on multiple sources such as sink broadcasting energy, co-channel interference, and neighbor nodes' RF signal. In this architecture, energy harvesting is done by each sensor in three ways: (a) from sink broadcast energy in time switching mode, (b) from its desired receiver node's RF signal in information receiving mode during power splitting mode, and (c) from any undesired neighboring nodes' RF signal which do not participate in the transmission or reception of information during power splitting mode.

(3) To minimize the energy consumption of the path, this work proposes a new routing mechanism that considers the minimum energy cost path.

(4) To validate the proposed method, this work executes extensive simulation experiments by varying different network parameters and the performance is analyzed through energy cost and aggregative energy cost.

The rest of this work is organized as follows. The literature related to this work is discussed in Section 2. The system model and modes used for transmission in SWIPT are described in Section 3. Proposed H-SWIPT technique is illustrated in Section 4. Energy-efficient route selection method is elaborated in Section 5. Simulation results of this work and their analysis are presented in Section 6. Finally, the conclusion is given in Section 7.

## 2 Related work

SWIPT is one of the emerging techniques to serve the energy needs of IoT networks. Hence, we reviewed different methods related to SWIPT for energy harvesting and routing in multi-hop IoT networks[11−13]. According to the methodology, the entire SWIPT techniques are categorized into three categories. They are SWIPT-PS, SWIPT-TS, and H-SWIPT methods. The details about these three categories are explored in the following subsections.

### 2.1 SWIPT-PS

He et al.[14] used the SWIPT-PS technique to improve the lifetime of the network by minimizing energy consumption. To reduce the energy consumption of a multi-hop wireless network, a routing algorithm has been proposed for forwarding the data with and without the SWIPT-PS technique. Here, past-hop node's RF signal is used to harvest the energy at the receiver node but it is not enough when the node density and barrier rate increase. H. S. Lee and J. W. Lee[15] proposed two algorithms for SWIPT based IoT systems to minimize the on-grid energy consumption. They are centralized-resource and task scheduling algorithm (C-RTA) and hybrid-resource and task scheduling algorithm (H-RTA). The authors used SWIPT-PS protocol to harvest the energy from hybrid access point (H-AP) and the harvested energy is distributed to $K$ number of IoT devices simultaneously. If the number of IoT devices increases, energy consumed by each device increases and the amount of harvested energy is not enough for information forwarding because it uses a single source.

Guo et al.[16] considered an energy efficiency optimization problem in clustered wireless sensor networks. The optimization was done based on the transmit power, PS ratio, and optimal relay selection. In their method, the cluster head node broadcasts the energy and information to its member nodes and chooses a member node that has a faster data rate as a relay node. However, the cluster head lost its energy and there is no alternate valid source for harvesting energy. Moreover, energy can only be harvested from the desired signal received by a cluster member node. The relay node cannot harvest enough energy to forward the information when the weak RF signal is received by the cluster head node and it impacts the network performance. Andrawes et al.[17] evaluated the downlink SWIPT-NOMA system performance. They used the PS technique to derive the expression for the signal to interference noise ratio (SINR) and outage probability for each near- and far end-user. The node which is nearer to the source is considered as an energy harvesting node. They also computed the energy consumption of the downlink NOMA system for a near and far user based on a specific SINR threshold value. If the distance between the near- and far-end user increases then the link reliability decreases and impacts the network performance.

Asiedu et al.[18] proposed a multi-hop decode-and-forward (DF) SWIPT mechanism to minimize the transmit power under various quality of service (QoS) constraints. Power splitting (PS) protocol is used to harvest the energy from the past-hop node's RF signals. The amount of harvested energy totally depends on transmitted signal and in the case of weak RF signal, they cannot harvest sufficient amount of energy. Han et al.[19] proposed a heuristic energy-efficient cooperative SWIPT routing algorithm based on the SWIPT-PS technique for 5G systems to find a transmission path with the maximum energy efficiency. For this purpose, they computed the path with minimum energy consumption. However, the harvesting energy depends only on the cluster head node's RF signal. They have not considered the cluster member nodes which are neither participated in transmission nor reception. Psomas and Krikidis[20] evaluated the impact of successive interference cancellation (SIC) on the SWIPT-PS performance in bipolar ad-hoc network. The main aim of SIC is that some signals related to interference may be strong enough to decode the information instead of removing from aggregated received signal. Chen et al.[21] formulated a novel optimization problem that minimizes the total networks energy consumption subject to the constraints like transmitting power and data transmission rate, CPU frequency, offloading weight factors, and energy harvesting weight factor. However, they considered only the single source for energy harvesting but not neighbor nodes' RF signal.

## 2.2 SWIPT-TS

Khan et al.[22] proposed an " energy efficient peer selection and time switching ratio allocation (EPS-TRA) algorithm" based on SWIPT-TS technique which considers the device-to-device (D2D) network links. Time switching protocol is used to harvest the energy and decode the information simultaneously to provide uninterrupted connectivity between the resource constrained nodes which in turn establishes the point-to-point communication between the devices. Total energy is harvested from past-hop node's RF signal and interfering signal energy from other D2D transmitters which operate at the same frequency. However, they did not explore the characteristics of the interference with varying strengths which has considerable impact over the harvested energy. Tang et al.[23] considered energy efficiency optimization problem in SWIPT-TS NOMA system for IoT networks. The harvesting energy totally depends on fixed energy source transmitted signal and time switching ratio. Moreover, the transmitted signal is shared among the $K$ terminals. In such condition, the amount of harvested energy is not sufficient to handle $K$ terminals, especially when the RF signal is weak. Tang et al.[24] considered an energy efficiency optimization problem for SWIPT multi-input multi-output (MIMO) broadcast channel using TS receiver. To increase the network transmission power, the authors tried to minimize the amount of energy harvested per user. The authors mainly concentrated on past-hop node's RF signal to harvest the energy and did not concentrate on remaining nodes' RF signals.

## 2.3 H-SWIPT

In Ref. [25], Ma et al. proposed a new SWIPT technique to improve the energy harvesting capacity of sensor nodes. They proved that the algorithm based on the time switching protocol is performed better than the algorithm based on the power switching protocol when the base station transmission power has been limited to a fixed quantity. The comparison between the PS protocol and TS protocol in terms of energy harvesting capacity is absent. They considered the integrated architecture for energy harvesting and the amount of harvested energy is not sufficient to transfer the data. Hu et al.[26] suggested a novel EH technique based on discrete-time-switch (DTS) and PS protocols to increase the average energy transfer rate and information rate. They focused on energy transfer rate but not on energy harvesting capacity.

In Ref. [27], Ofori-Amanfo et al. proposed multi-hop MIMO relaying based on SWIPT by integrating TS and PS protocols. The current relay depends on the immediate preceding relay node's RF signal to harvest the energy. They investigated the minimum amount of energy harvested at each node under various schemes. From simulation results, it has been observed that a node near the source harvests more energy than the node away from the source. So as the distance from the source node increases, harvesting energy decreases and results in degraded network performance. Fan et al.[28] proposed a multi-hop DF SWIPT mechanism for relay network with wireless energy harvesting to maximize the throughput and energy harvesting capacity. The authors used TS and PS protocols to harvest the energy and introduced two strategies: varying TS and PS ratios and uniforming TS and PS ratios at each relay node. Single source, i.e., past-hop node's RF signal, is used to harvest the energy in each scheme and not concentrated on remaining nodes' RF signal. Lakshmi and Jibukumer[29] examined the performance of multi-hop IoT networks using TS and PS relaying schemes. From their numerical analysis, it has been seen that PS protocol executes better than TS protocol for higher value of the signal to noise ratio (SNR) whereas TS protocol executes better than PS protocol for lower value of SNR.

**Problem outline:** By reviewing all of the above existing methods, we observed that only past-hop node RF signal is used to harvest the energy in SWIPT for multi-hop IoT networks and they did not consider the remaining nodes or neighbor nodes' RF signal. Here, the neighbor nodes are the nodes that neither transmit nor receive any information and remain idle in the network. They can also be considered as a valid source of energy to improve the energy harvesting capacity but most of the earlier methods did not concentrate in that direction. Moreover, most of the methods did not consider interference as a source of energy harvesting. Even sink node can also contribute towards energy harvesting as it has continuous energy supply, but none of the methods concentrated in this aspect.

## 3 System model

This section describes the network model and modes of transmission. Initially, we discuss the network model through different components of the network such as sensor nodes, sink node, and end user. Further, we discuss the two possible transmission modes such as information transmission (IT) and SWIPT.

### 3.1 Network model

This paper considers an architecture for a multi-hop wireless IoT network, as shown in Fig. 1, with $N$ sensors and one sink node. Each sensor in the network acts as an information and energy transmitter. Each sensor in the network is equipped with a single antenna. The sink node is treated as the network's central controller to handle the queries like routing and signaling. The sink node not only collects the information from every sensor in the network but also broadcasts the energy to all. The so-called network is similar to the directed graph. The directed graph $G = (N, L)$ consists $N$ vertices or sensor nodes and $L$ edges or links. A directed link between any two nodes (e.g., $i$ and $j$) is valid only when the Euclidean distance ($d_{ij}$) between them is less than or equal to the communication range ($r$), i.e., $d_{ij} \leqslant r$. The transmission range of sensors varies with the transmission power of each sensor. This work considers the channel model as quasi-static Rayleigh flat fading[30, 31] with imperfect channel state information (CSI)[32, 33] and the receiver's antenna noise is additive white Gaussian noise (AWGN). The notations used in this paper are tabulated in Table 1.

### 3.2 Modes of transmission

In energy-constrained multi-hop IoT networks using SWIPT for end-to-end communication, the routing links are either information transmission (IT) links or SWIPT links. IT link or IT mode of transmission is used to transmit only information whereas SWIPT link or SWIPT mode of transmission is used for simultaneous transfer of both information and power.

#### 3.2.1 IT mode

In simultaneous wireless information and power transfer, both the transmitter and receiver are equipped with a single antenna. Here, the sender node $i$ transmits its baseband signal $x(t)$ to the receiver node $j$ through a wireless channel with channel gain coefficient $h_{ij}$. Here $x(t)$ is considered as a narrowband signal having power $P_{ij}$ and $E[|x(t)|^2]$ is one. The channel power gain coefficient $h_{ij}$ includes path loss, shadowing, and fading effects of the channel. The circuit used for the information decoder[34] is shown in Fig. 2. The LPF is a low pass filter and ADC is an analog to digital converter. The RF signal power received by the

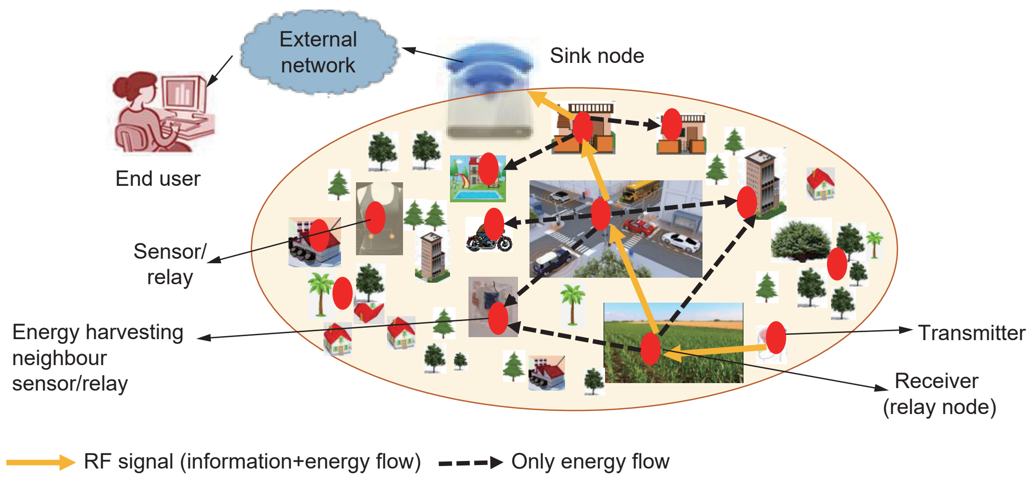


**Fig. 1 Network model.**

**Table 1 List of notations.**

| Notation | Description |
|---|---|
| $P_{ij}$ | Transmission power from node $i$ to node $j$ |
| $N$ | Number of sensor nodes |
| $h_{ij}$ | Channel power gain between node $i$ and node $j$ |
| $\gamma_{ij}$ | Signal to noise ratio (SNR) for IT |
| $\gamma_{ij}^{SWIPT\text{-}PS}$ | SNR for SWIPT-PS |
| $\gamma_{min}$ | Minimum SNR ratio requirement |
| ${\sigma_{ij}}^2$ | Power of antenna noise from node $i$ to node $j$ |
| ${\sigma_C}^2$ | Power of signal conversion noise from node $i$ to node $j$ |
| $\varepsilon$ | Energy harvesting coefficient of node $j$ |
| $\rho_{ij}^{I}$ | Power splitting ratio for ID |
| $\rho_{ij}^{E}$ | Power splitting ratio for EH |
| $a_{ij}$ | A binary variable indicates whether the receiver node harvests energy from an undesired transmitter node or not |
| $b_{ij}$ | A binary variable indicates whether the specified link is active or not |
| $E_{ij}^{eh}$ | Energy harvesting power from node $i$ to node $j$ |
| $T$ | Time required to collect the information |
| $\alpha$ | Time required to broadcast the sink node energy |
| $t$ | Time required to transmit the information |
| $m$ | Total number of IT slots |
| $s$ | Number of nodes where node $j$ is used as a relay node |
| $\eta_{ij}$ | Energy conversion efficient |
| $\sigma_{I,ij}^2$ | Co-channel interference |
| $P_{sb}$ | Sink broadcast power |
| $Preq_j$ | Minimum EH power requirement for forwarding by receiver node $j$ |
| $n$ | Number of undesired neighbor nodes |
| $P_{max}$ | Maximum transmission power |
| $\delta_{ij}$ | Priorities of different receiver nodes |
| $E_T^{eh}$ | Total energy harvested at the receiver node |
| $br$ | Barrier rate |
| $Er_{min}$ | Minimum energy requirement for forwarding |

receiver at node $j$ is given by

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

where $n_{A,ij}$ is the noise emitted from receiving antenna having mean as zero and variance as ${\sigma_{ij}}^2$. Information decoder circuit has two parts: in the first part the RF signal received by the receiver node $j$ is converted into a complex baseband signal and it introduces signal conversion noise $n_{C,ij}$, and in the second part, the complex baseband signal is sampled and digitalized by an analog-to-digital converter to decode the information. Here, we assume an ideal analog-to-digital converter with zero noise. So, the output of the analog-to-digital converter is given by

$$\widehat{y}(k) = \sqrt{P_{ij}}h_{ij}x[k] + n_{A,ij}[k] + n_{C,ij}[k] \tag{2}$$

where $n_{C,ij}$ is signal conversion noise having mean as zero, variance as ${\sigma_C}^2$, and $k$ indicates symbol index which is equal to 1, 2, 3,…, and so on. The signal to noise ratio (SNR) of digitalized information is given by

$$\gamma_{ij} = \left|h_{ij}\right|^2 P_{ij}/({\sigma_{ij}}^2 + {\sigma_C}^2) \tag{3}$$

This work considers decode-and-forward (DF) protocol. According to this protocol in an energy-constrained multi-hop IoT network to decode the information at the receiver node successfully, the signal to noise ratio (SNR) of the received signal should be greater than the minimum signal to noise ratio requirement. If it satisfies the above condition based on the EH power requirement of receiver node, it will forward the information to the next node successfully.

### 3.2.2 SWIPT-PS mode

The receiver architecture of the power splitting mode of SWIPT (SWIPT-PS) has two circuits, namely, EH circuit and ID circuit. The received signal at node $j$ is divided into two halves using a power splitter with an unequal amount of power. One halve of power is

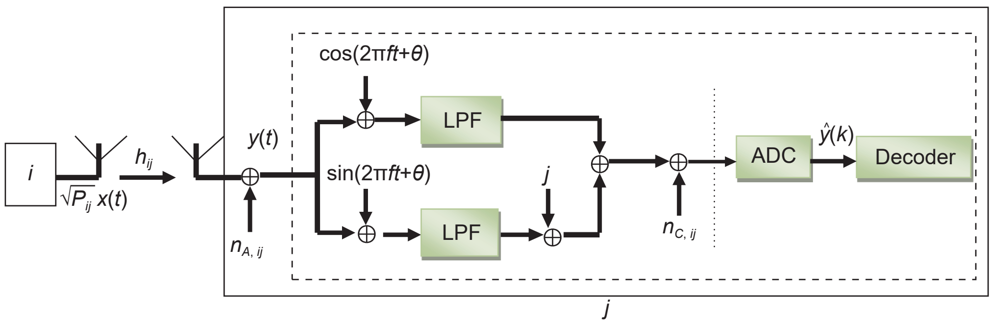


**Fig. 2 Circuit diagram for information transmission.**

transferred to EH circuit and the other is transferred to ID circuit, as shown in Fig. 3.

In the SWIPT-PS, the baseband signal $x(t)$ at node $i$, the wireless channel between the node $i$ and node $j$, and RF signal $y(t)$ at the node $j$ are all similar to those of information transmission mode. Based on the power splitting ratio, the fraction $\rho_{ij}^E$ power amounts to EH and the other fraction $\rho_{ij}^I$ power amounts to ID. The part of power used for the EH circuit after splitting is indicated with $y^{EH}(t)$ and it is given by

$$y^{EH}(t) = \sqrt{\rho_{ij}^E}y(t) = \sqrt{\rho_{ij}^E}\left(\sqrt{P_{ij}}h_{ij}x(t) + n_{A,ij}(t)\right) \tag{4}$$

According to Refs. [14, 30 ], the energy harvested power at node $j$ is given by

$$E_{ij}^{eh} = \varepsilon\left(\rho_{ij}^E\right)\left(\left|h_{ij}\right|^2 P_{ij} + {\sigma_{ij}}^2\right) \tag{5}$$

where $\varepsilon$ is energy harvesting coefficient of EH circuit and $\varepsilon \in [0, 1]$. At the same instant, the remaining part of power is transferred to the information decoding circuit and it is indicated with $y^{ID}(t)$ which is given by

$$y^{ID}(t) = \sqrt{\rho_{ij}^I}y(t) + n_{C,ij}(t) = \sqrt{\rho_{ij}^I}\left(\sqrt{P_{ij}}h_{ij}x(t) + n_{A,ij}(t) + n_{C,ij}(t)\right) \tag{6}$$

The SNR of SWIPT-PS is given by

$$\gamma_{ij}^{SWIPT\text{-}PS} = \rho_{ij}\left|h_{ij}\right|^2 P_{ij}/({\sigma_{ij}}^2 + {\sigma_C}^2) \tag{7}$$

## 4 Proposed method

### 4.1 Overview

This work considers the hybrid protocol of SWIPT for EH to improve the lifetime of an IoT network. According to Fig. 1, a source node sends information to the sink or destination node through multiple paths using relay nodes and neighboring nodes within specified time intervals. The amount of energy harvested in the present time interval is deposited into their rechargeable battery in the next time interval for future usage. They harvest the energy, store it in a rechargeable battery and then cooperate[35, 36]. Here, assume some energy is given to all the sensor nodes initially.

Each sensor node has operated in three modes. They are information transmission (IT) mode, information reception (IR) mode, and energy harvesting (EH) mode, but only one mode is triggered at a time within its specified time interval. In IT mode, the transmitting node transmits both energy and information in the given transmitting interval. In IR mode, the relay node uses PS protocol and splits the RF signal into two streams based on the power splitting ratio. Among them, one signal stream is used for ID and another for EH simultaneously in its receiving time interval. In EH mode, the sensor node harvests the energy from other neighbor transmitting nodes (undesired transmitters or receivers) in its time interval. Hence, the proposed technique is used to harvest additional energy using neighbor nodes and co-channel interference unlike the conventional SWIPT-PS technique harvesting energy only in IR mode.

### 4.2 H-SWIPT-MS

The sink node gathers information in the collection period $(p_1, p_2, \ldots, p_k)$ from all the sensors which are

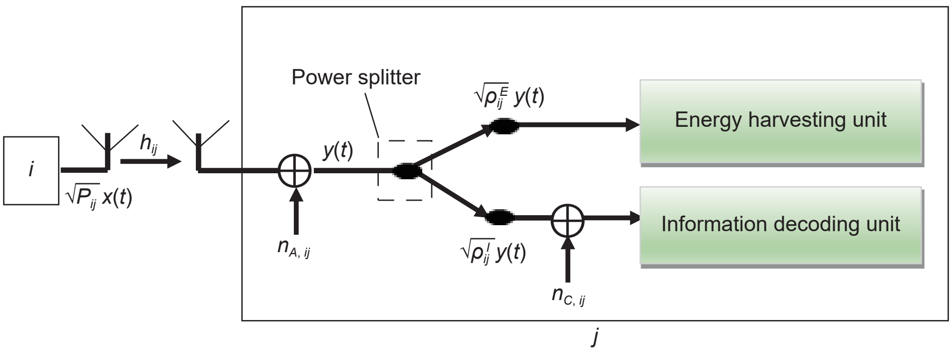


**Fig. 3 Circuit diagram for SWIPT-PS.**

located in its communication range ($r$). Here each information collection period has an equal time interval $T$ ($|p_1| = |p_2| = |p_k| = T$) and this interval $T$ is split into two unequal time durations based on the time splitting ratio. One time duration $\alpha$ is for energy broadcasting by the sink node and another time duration $(T-\alpha)$ is for information transmission. Furthermore, $(T-\alpha)$ time duration is divided equally into $m$ information transmission time slots among $N$ sensors having equal time interval $t$ ($|t_1| = |t_2| = \cdots = |t_m| = t$). Here maximum $m$ sensor nodes information transmits simultaneously when it holds $(\alpha + mt) \leqslant T$ inequality as illustrated in Fig. 4.

Each sensor node in the network consists of EH unit, ID unit, PS unit, TS unit, and a rechargeable battery. Due to the few constraints in hardware[37] during practical operations in the receiving sensor, the

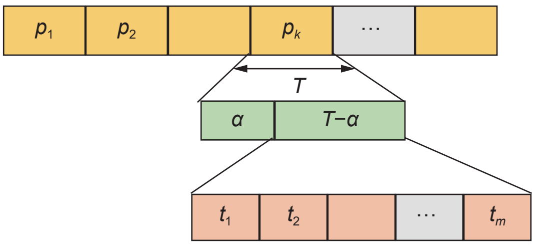


**Fig. 4 Structure of time slot (*T*).**

circuitry used for the signal processing unit is unable to attach with EH unit. So, the EH and ID units are separated from each other as illustrated in Fig. 5. Here, the power loss and noise produced by TS and PS units at the time of signal processing are not taken into account. Here, the energy consumed during data reception is neglected because a negligible amount of energy is needed to receive the information than the transmission.

For example, consider three sensor nodes and one sink node. Three sensor nodes are the transmitting node, receiving node, and neighbor node. Based on these nodes, the working principle of the proposed H-SWIPT technique is described and it is shown in Fig 5. In each $t$-th time interval, the sensor node in the network can operate in any one of three modes: IT, IR, and EH. Here, assume node $i$ is treated as the transmitter node and node $j$ is treated as the receiver node. The energy harvested by the receiver node $j$ in each time interval is deposited for future usage in their rechargeable battery. Based on the PS and TS protocols, the working steps of proposed method are described below.

(1) The sink node broadcasts energy in $\alpha$ time duration in TS mode as shown with dotted lines in

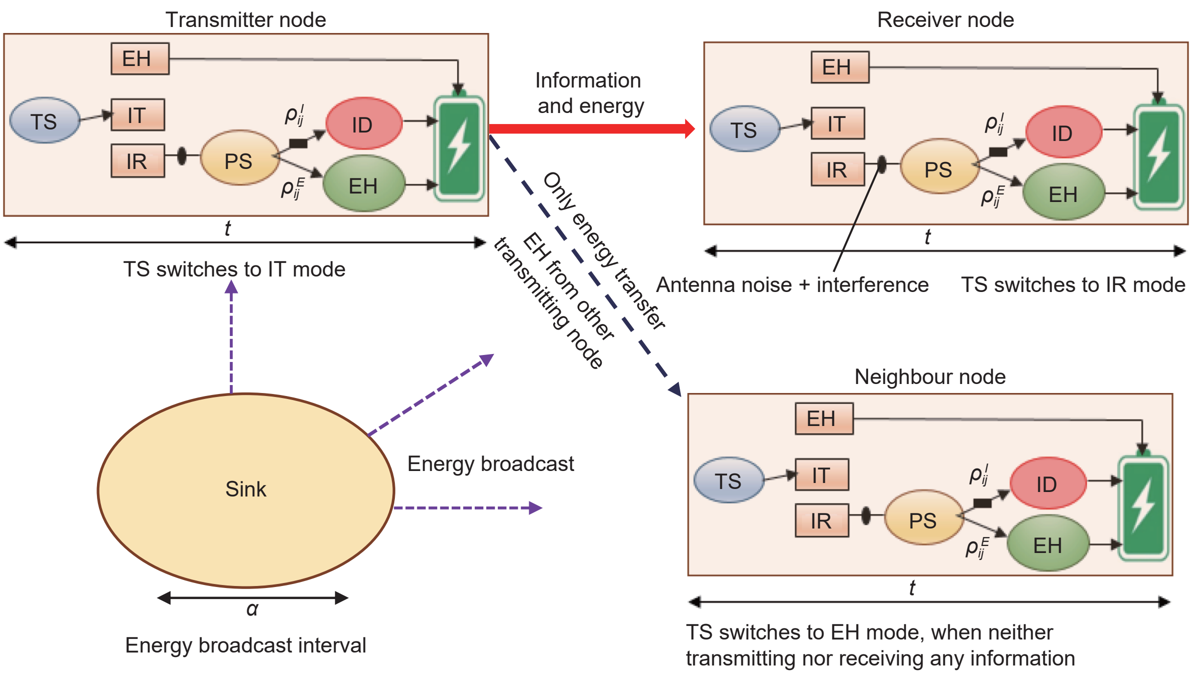


**Fig. 5 Architecture of H-SWIPT.**

Fig. 5. In this duration, all sensors in the network harvest energy at a time from the sink node.

(2) The following operations are done in the $t$-th time interval independently (not at a time) and it is illustrated in Fig. 5.

(a) When the time switcher is shifted to IT mode, as shown in Fig. 5, both energy and information are simultaneously transmitted to the desired receiver node $j$ from the transmitter node $i$ (indicated with red solid arrow). During this time neighbor nodes (undesired receiver nodes) receive only energy (indicated with a blue dotted arrow).

(b) When the time switcher is shifted to IR mode, at the power splitter unit the received RF signal is divided into two streams: ratio $\rho_{ij}^{E}$ and $\rho_{ij}^{I}$ for simultaneous energy harvesting and information decoding, respectively, where $\rho_{ij}^{E} \in [0, 1]$ and $\rho_{ij}^{I} \in [0, 1]$ such that $\rho_{ij} = (\rho_{ij}^{I} + \rho_{ij}^{E}) \leqslant 1$.

(c) When the time switcher is shifted to EH mode, the sensor node harvests energy from the undesired neighbor nodes (neither transmitting nor receiving) RF signal irrespective of the sink.

Figure 6 shows the working flow of the proposed SWIPT technique. Initially, in time interval $\alpha$ the sink node broadcasts RF signal in the network area and the remaining nodes harvest energy from it. Later, in time duration $t$, the transmitter, receiver, and remaining nodes work in parallel.

According to our proposed H-SWIPT architecture, we calculate the total energy harvested by each sensor in the given network in time interval $T$. The total energy harvested is denoted with $E_T^{eh}$ and given by

$$E_T^{eh} = E_{max} + E_{NI} + E_{SN} + E_{NN} \tag{8}$$

(1) $E_{max}$: In time duration $T$, the maximum energy harvested by the receiver $j$ from desired transmitter $i$ is given by

$$E_{max} = \sum_{i=1}^{s} P_{ij} \varepsilon \eta_{ij} \rho_{ij}^{E} h_{ij} t, s \in N \tag{9}$$

where $s$ is a collection of transmitting sensor nodes where node $j$ is treated as a relay, $P_{ij}$ is transmitting power, $\varepsilon$ is energy harvesting coefficient ($0<\varepsilon<1$), $\eta_{ij}$

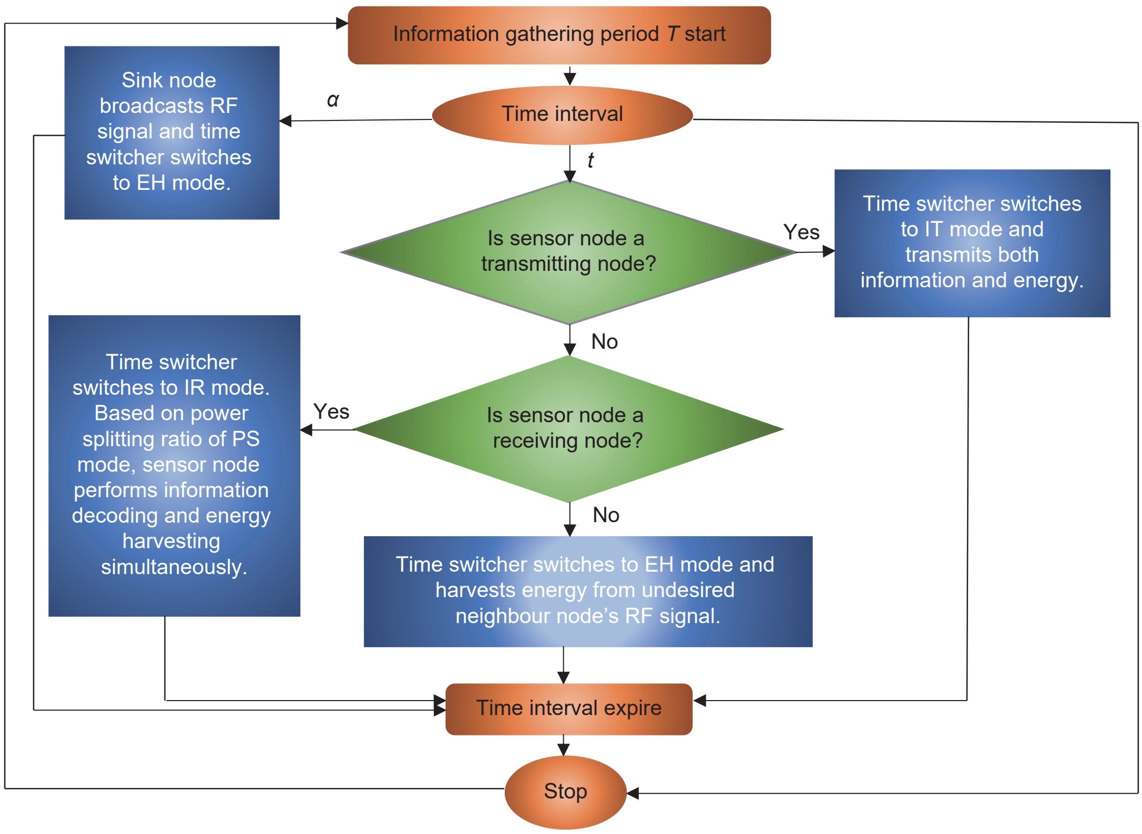


**Fig. 6 Working flow of H-SWIPT.**

is energy conversion coefficient ($0<\eta_{ij}<1$), $\rho_{ij}^{E}$ is power splitting ratio for EH, and $h_{ij}$ is channel power gain coefficient.

(2) $E_{NI}$: In time interval $T$, the amount of energy harvested while gathering information due to the presence of co-channel interference and antenna noise at receiver node $j$ is given by

$$E_{NI}=\sum_{i=1}^{s}(\sigma_{I,ij}^{2}+\sigma_{ij}^{2})\eta_{ij}\rho_{ij}^{E}t \tag{10}$$

where $\sigma_{I,ij}^{2}$ indicates co-channel interference at receiver node $j$ and $\sigma_{ij}^{2}$ represents the variance of antenna noise (AWGN).

(3) $E_{SN}$: In time interval $\alpha$, the amount of energy harvested by receiver node $j$ from sink broadcasting power $P_{sb}$ is given by

$$E_{SN}=P_{sb}\varepsilon\eta_{ij}h_{ij}\alpha \tag{11}$$

(4) $E_{NN}$: In time interval $T$, the amount of energy harvested by receiver node $j$ from $n$ undesired neighboring nodes which are neither transmitting nor receiving nodes is given by

$$E_{NN}=\sum_{i=1}^{n}P_{ij}\varepsilon\eta_{ij}h_{ij}t\left(1-b_{ij}\right), n\in N \tag{12}$$

where $b_{ij}$ is a binary indicator. If it is equal to one, the relay node $j$ cannot harvest energy from undesired neighbor sensor node $i$ because these undesired neighbor sensor nodes are either transmitting information to their desired receiver (not relay $j$) or receiving information from their transmitter.

## 5 Routing

Energy-efficient routing schemes play a significant part to enhance the lifetime of an IoT network. These schemes select the best path for data transmission as well as energy consumption in the network. In this work, the energy cost metric $E_C$ is introduced to evaluate the link and path energy consumption. The IT and SWIPT transmission links are available in energy-constrained multi-hop IoT networks. Let us assume the transmitting node $i$ sends information through the link $l_{ij}$ with IT to the receiver node $j$. We consider $E_C$ of the link $l_{ij}$ with IT is $E_{C(i,j)}^{IT}$ and it is equivalent to the power $P_{ij}$.

$$E_{C(i,j)}^{IT}=P_{ij} \tag{13}$$

Here, to decode the information at the receiver node successfully, the SNR ($\gamma_{ij}$) should be not less than the minimum signal to noise ratio requirement denoted by $\gamma_{min}$. So,

$$\gamma_{ij}\geqslant\gamma_{min} \tag{14}$$

So, from Eqs. (3) and (13), and Formula (14), the minimum $E_{C(i,j)}^{IT}$ is given by

$$E_{C(i,j)}^{IT}\geqslant({\sigma_{ij}}^{2}+{\sigma_{C}}^{2})\gamma_{min}/\left|h_{ij}\right|^{2} \tag{15}$$

Let us assume the transmitting node $i$ sends information through the link $l_{ij}$ with H-SWIPT to the receiver node $j$, some amount of power from the transmitting node is converted to energy at the receiver node and it is not consumed during the transmission. Hence, the total energy cost of the link $l_{ij}$ with H-SWIPT is $E_{C(i,j)}^{H\text{-}SWIPT}$ and it is given by

$$E_{C(i,j)}^{H\text{-}SWIPT}=P_{ij}-E_{T}^{eh} \tag{16}$$

Furthermore, the receiver node $j$ tries to forward the information to the next node. Before going to forward the information to the next node, it will verify the $j$-th node minimum energy harvesting power requirement $Preq_j$. To forward the information from the receiver node to the next node successfully, the following condition should be satisfied.

$$E_{T}^{eh}\geqslant Preq_{j} \tag{17}$$

Here, $Preq_j$ depends on different distances and channels between the receiver node and the next node. So, the $j$-th node energy harvesting power requirement is equal to the transmission power from node $j$ to its next-hop node denoted by $k$.

$$Preq_{j}=P_{jk},\ \text{s.t.}\ a_{jk}=1 \tag{18}$$

In SWIPT, the amount of information transmission or energy harvesting is decided based on PS and TS ratios. Hence, Eq. (16) is reformulated as

$$E_{C(i,j)}^{H\text{-}SWIPT}=P_{ij}-\rho_{ij}^{E}E_{T}^{eh} \tag{19}$$

Using Eq. (19), based on splitting ratio, the receiver node $j$ can decide whether to choose IT mode or H-SWIPT mode of transmission. If the splitting ratio $\rho_{ij}^{E}=0$, only information transmission (IT) takes place between node $i$ and $j$, otherwise based on the value of splitting ratio, both information transmission and energy harvesting take place simultaneously. So, the total energy consumed for the path from source to the destination is equivalent to the sum of energy consumption of all links in the corresponding path.

$$E_{Total(s,d)} = \sum_{l_{ij} \in path_{sd}} E_{C(i,j)}^{H\text{-}SWIPT} \tag{20}$$

Let us assume one binary variable $a_{ij}$, if it is equal to one, the link between the nodes $i$ and $j$ is active for the path from source to the destination, otherwise the path is inactive. Therefore, our objective is to find a path from source to destination with the minimum energy cost. So, our problem is reformulated as

$$f(x) = \min_{\rho,P} \sum\nolimits_{l_{ij}} a_{ij}(P_{ij} - \rho_{ij}^{E} E_{T}^{eh}) \tag{21}$$

$$\text{s.t. } \gamma_{ij} \geqslant \gamma_{min}, \forall i, j,$$

$$E_{T}^{eh} \geqslant Preq_{j}, \forall i, j,$$

$$Preq_{j} = P_{jk} \text{ if } a_{jk} = 1,$$

$$P_{ij} \in [0, P_{max}], \forall i, j,$$

$$\rho_{ij}^{E} \in [0,1],\ \rho_{ij}^{I} \in [0,1] \text{ and}$$

$$\rho_{ij} = \rho_{ij}^{I} + \rho_{ij}^{E} \leqslant 1,$$

$$a_{ij} \in \{0,1\}, \forall i, j, \alpha > 0, T > 0, \alpha + mt \leqslant T, i, j \in [1, 2, \ldots, N].$$

Equation (21) determines the minimum energy cost path for a given source and destination node pair. For this determination starting from source node, each next-hop node finds next-hop neighbor node based on minimum energy cost which is related with $\gamma_{ij}$. Here, the $\gamma_{ij}$ must be greater than $\gamma_{min}$. At the same time, the sender node checks the $Preq_j$ of the $j$-th receiver node. If $E_T^{eh} \geqslant Preq_j$, the $j$- th receiver node forwards the information as it is after receiving from sender node, otherwise it harvests energy and then forwards. The $Preq_j$ directly depends on its next-hop node forwarding capacity in terms of power denoted by $P_{jk}$. At the same time, the sender node checks the status of the link through $a_{jk}$ ("1" denotes active and "0" denotes inactive). Further, each node transmits power $P_{ij}$ that should be in the range of 0 and $P_{max}$.

The amount of power required for energy harvesting and information decoding at each node is decided by $\rho_{ij}^E$ and $\rho_{ij}^I$ and it must be in the range of 0 and 1 such that $\rho_{ij} = (\rho_{ij}^I + \rho_{ij}^E) \leqslant 1$. Sink broadcast time interval $\alpha$ and total time interval $T$ must be greater than zero for all the time. The time required for sink broadcasting and maximum $m$ nodes information transmission must be less than or equal to $T$, i.e., $\alpha + mt \leqslant T$. The clear demonstration about the energy efficient routing assisted with H-SWIPT-MS is depicted in Algorithm 1.

## 6 Simulation results and analysis

In this section, we explore the details of experimental analysis carried out over the proposed method. Initially, we explain the details of simulation scenario and then the results obtained.

### 6.1 Simulation scenario

For the simulation purpose, we used MATLABR2021a as a simulation tool. For the implementation of proposed method, initially we create a random network through the MATLAB function "rand" . Further, we used some more MATLAB functions, namely, NetArch (length, width, sink-location, and initial energy) and NodeArch (NetArch and number of nodes).

We consider the number of nodes varying from 20 to

**Algorithm 1 H-SWIPT-MS routing**

**Input:** $G(N, L)$ , $\gamma_{min}$, $P_{max}$, destination ($D$)

**Output:** minimum energy consumed path from $i$ to $D$, with each hop $(i, j)$ and $\rho_{ij}^E$, $P_{ij}$

```
F_i ← { }
W ← ∅
P ← N
while P ≠ ∅ do
    j ← EXTRACT − MIN(P)
        W ← W ∪ {j}
    for each incoming edge (i, j) ∈ L do
        if E_{C_i} > E_{C_j} then
            ρ^E_{ij} ≠ 0; E*_{C_i} = P_{ij} − E^{eh}_T + E_{C_j}
        else
            ρ^E_{ij} = 0; E*_{C_i} = P_{ij} + E_{C_j}
        end if
            if E_{C_i} > E*_{C_i} then
                E_{C_i} ← E*_{C_i}
                F_i ← j
                Preq_i ← P_{ij}
            end if
    end for
end while
```

70, and they are located over the area of 100×100 $m^2$. We consider that priority of all receiving nodes is equal, i.e., $\delta_{ij} = 1, \forall i, j \in d_{ij}$ and the communication channel is small-scale Rayleigh flat fading. The maximum transmitting power ($P_{max}$) is 100 mW. We set the minimum harvest energy to be 10% of $P_{max}$ and the minimum energy requirement for forwarding ($Er_{min}$) the information is 0.4 mJ. We consider that all nodes in the network have the same noise parameters. The remaining parameters used for simulation is listed in Table 2.

### 6.2 Simulation results

Under this section, the performance of H-SWIPT-MS is compared with SWIPT-PS[14], SWIPT-TS[24], and H-SWIPT using single source (H-SWIPT-SS)[28] and IT[34]. For comparison, we use three metrics, they are average harvested energy (AHE), energy cost, and aggregative energy cost. AHE is calculated as the sum of energy harvested at each node divided by total number of nodes on the path. Next, energy cost is calculated as the total energy consumed over a route from source to destination. Further, aggregative energy cost is the sum of all other nodes energy cost from source to destination. To validate the performance of H-SWIPT-MS, four sets of simulation experiments are conducted by varying maximum transmit power, barrier rate, the minimum energy required for forwarding, and node density.

**Table 2 List of parameters used for simulation.**

| Parameter | Value |
|---|---|
| $\lvert h_{ij}\rvert^2$ | 1 |
| $\gamma_{min}$ | 20 dB |
| $\sigma_{ij}^2$ | −50 dBm |
| $\sigma_C^2$ | −70 dBm |
| $\varepsilon$ | 0.65 |
| $T$ | 30 s |
| $t$ | 1 s |
| $m$ | 25 |
| $s$ | 5 |
| $\eta_{ij}$ | 0.8 |
| $\sigma_{I,ij}^2$ | 10 dBm |
| $br$ | 30% |
| $Er_{min}$ | 0.4 |
| $n$ | 5 |
| $P_{max}$ | 100 mW |

Figure 7 shows the AHE for varying maximum transmit power. The AHE of proposed H-SWIPT-MS is compared with SWIPT-PS[14], SWIPT-TS[24], and H-SWIPT-SS[28]. As the maximum transmitted power increases, the sensor needs to harvest more energy. From Fig. 7, it can be seen that all the methods harvesting an increased amount of energy but they are not able to harvest sufficient amount of energy as they use only single source. In this regard, the proposed method harvested more energy and it is approximately 0.836 J while SWIPT-PS, SWIPT-TS, and H-SWIPT-SS harvested 0.636 J, 0.434 J, and 0.684 J, respectively.

Figure 8 shows the AHE for varying interference levels ranging from 0 dB to 15 dB. As our method considered, interference as one of the sources for energy harvesting, we analyzed the performance of proposed method through AHE at various interference

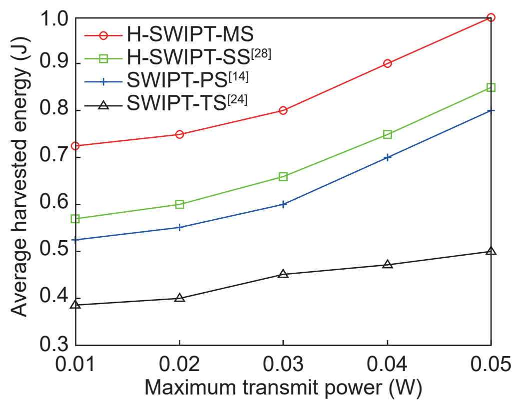


**Fig. 7 AHE comparison with varying maximum transmit power.**

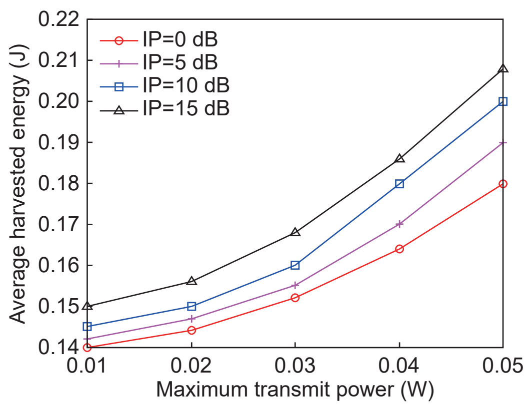


**Fig. 8 AHE for varying interference levels.**

levels. From the results, the proposed method harvested more energy for larger interference and vice versa.

### 6.2.1 Impact of node density

Figure 9a shows the impact of node density on energy cost. This case study considers 20 to 70 nodes to estimate the effect of node density on the energy cost. When the number of nodes is increasing from 20 to 70 the energy cost of all routing schemes is decreasing gradually. But when the number of nodes increases from 30 to 60, the energy cost of H-SWIPT-MS starts decreasing more than remaining techniques. Hence, H-SWIPT-MS has shown better results compared to other techniques at higher node density because of the decrease of active nodes to forward the information. Forwarding packets through the lesser energy nodes is the major advantage of H-SWIPT-MS. From the results, we observed the percentage of average improvement in the reduction of energy cost for H-SWIPT-MS with H-SWIPT-SS, SWIPT-PS, SWIPT-TS, and IT is 6.38%, 12.5%, 16.38%, and 20.91%, respectively. Further, Fig. 9b proves the effectiveness of proposed method in terms of aggregative energy cost for varying node density. On an average, the percentage of improvement in the reduction of aggregative energy cost for H-SWIPT-MS with H-SWIPT-SS, SWIPT-PS, SWIPT-TS, and IT is observed as 11.55%, 23.10%, 29.43%, and 35.74%, respectively.

### 6.2.2 Impact of minimum energy requirement for forwarding ($Er_{min}$)

Figure 10a shows the energy cost for varying $Er_{min}$ for different methods. When the residual energy of a node is less than $Er_{min}$, the number of inactive nodes increases and shows significant impact on the performance of network. For the simulation purpose, $Er_{min}$ is varied from 0.1 to 0.6 and observed an increasing energy cost with an increasing $Er_{min}$. If $Er_{min}$ increases, the number of active nodes decreases

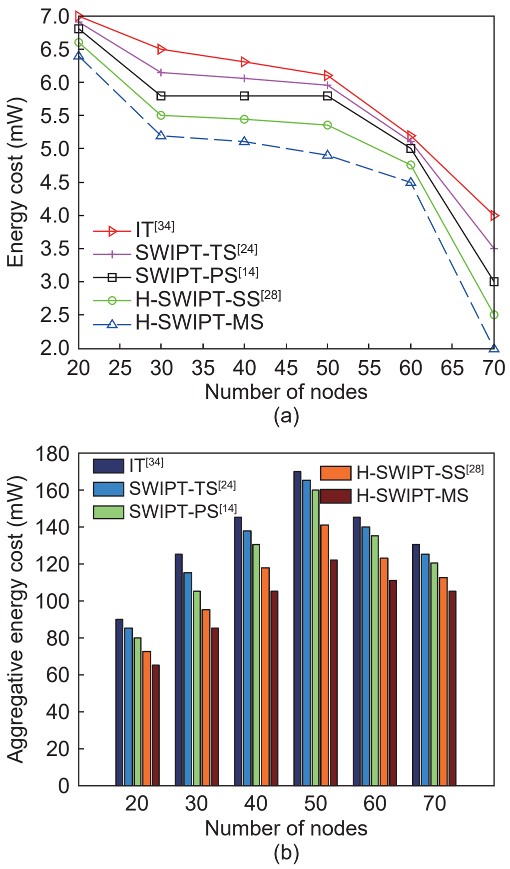


Fig. 9 Effect of node density. (a) Effect of node density on energy cost; (b) Effect of node density on aggregative energy cost.

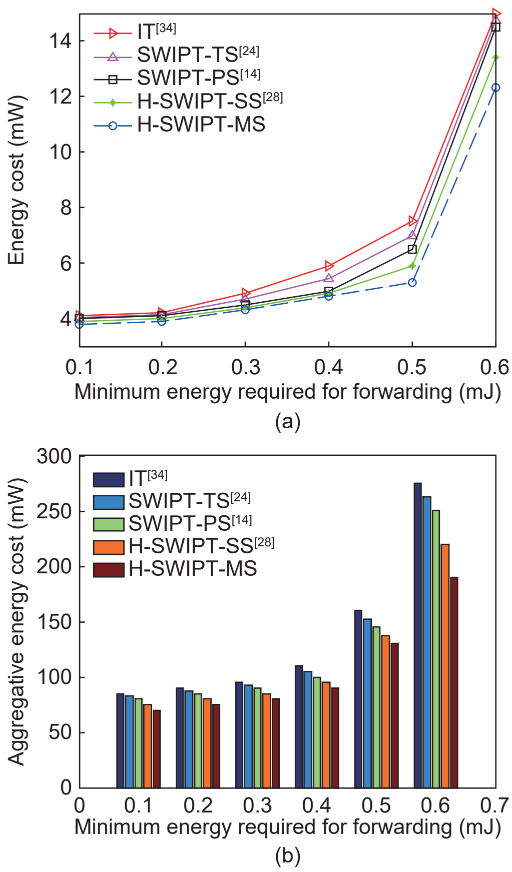


Fig. 10 Effect of minimum energy required for forwarding. (a) Effect of minimum energy requirement for forwarding on energy cost; (b) Effect of minimum energy requirement for forwarding on aggregative energy cost.

and energy cost increases. When $Er_{min}$ is equal to 0.2, the energy cost of all methods is approximately equal because of the huge availability of active nodes to forward the information. But when it increases from 0.2 to 0.6, the energy cost also increases due to the availability of less active nodes to forward the information. At this point, H-SWIPT-MS has shown good results compared to existing methods because it uses the minimum energy cost path. On an average, the percentage of improvement in the reduction of energy cost for H-SWIPT-MS with H-SWIPT-SS, SWIPT-PS, SWIPT-TS, and IT is observed as 4.95%, 10%, 13.3%, and 17.24%, respectively. Further, Fig. 10b proves the effectiveness of proposed method in terms of aggregative energy cost for varying $Er_{min}$. From the results, the percentage of average improvement in the reduction of aggregative energy cost for H-SWIPT-MS with H-SWIPT-SS, SWIPT-PS, SWIPT-TS, and IT is 8.7%, 16%, 21.54%, and 22.22%, respectively.

### 6.2.3 Impact of barrier rate (*br*)

Under this case study, we consider barrier rate (*br*) to validate the network performance and it is defined as the percentage of unavailability of the direct link between the nodes. Figure 11 describes the impact of barrier rate (*br*) on the network performance through energy cost and aggregative energy cost. The range of barrier rate is varied from 0.1 to 0.6. When the barrier rate increases, the energy cost and aggregative energy cost also increase due to the unavailability of direct links. When *br* is 0.1, the energy cost of all methods is approximately equal due to more direct links availability. When the barrier rate increases from 0.1 to 0.6, the number of direct links availability decreases. At this point, more hops are required for a node to forward the data. From the results, we observed an average improvement in the reduction of energy cost for H-SWIPT-MS with H-SWIPT-SS, SWIPT-PS, SWIPT-TS, and IT is 12.43%, 24.57%, 31.07%, and 56.25%, respectively. At the same time, the reduction of aggregative energy cost for H-SWIPT with H-SWIPT-SS, SWIPT-PS, SWIPT-TS, and IT is 7.69%, 13.67%, 16.08%, and 20%, respectively.

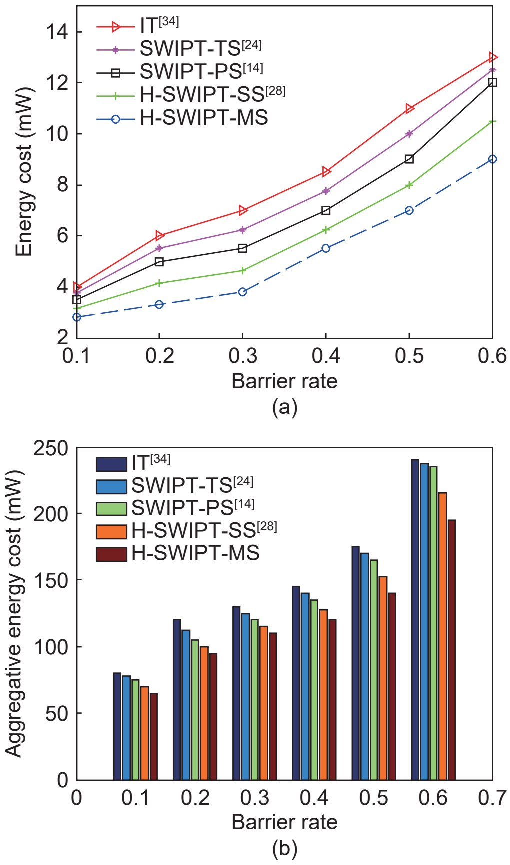


**Fig. 11 Effect of barrier rate. (a) Effect of barrier rate on energy cost; (b) Effect of barrier rate on aggregative energy cost.**

## 7 Conclusion

The energy consumption of the IoT network increases due to an uninterrupted sensor devices operations. Even though continuous energy supply is one of the solutions but it is not possible for all the cases when the sensors are deployed in a resource-constrained environment. To sort out this problem, we proposed a new energy harvesting mechanism using H-SWIPT-MS technique which includes multiple sources like sink node, undesired neighbor nodes, and co-channel interference to improve the energy harvesting capacity. Furthermore, an efficient route selection mechanism is proposed based on energy cost metric to minimize the energy consumption. Validation of the proposed method is done through various simulation experiments. The performance effectiveness of the proposed method is validated through AHE, energy cost, and aggregative energy cost at different network environments including varying node count, barrier rate, and $Er_{min}$. The obtained results prove the outstanding performance compared to the state-of-the-art methods.

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