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Energy-Constrained Route Selection Mechanism Using Hybrid SWIPT for IoT Networks

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Abstract: Sensors in an internet of things (IoT) network are energy-consuming devices and they operate on batteries that have limited energy capacity. This issue impacts the network lifetime. One of the promising solutions for this problem is simultaneous wireless information and power transfer (SWIPT). In SWIPT, a receiver node harvest the energy by itself based on the quantity of RF signal. When the transmitted RF signal becomes weak, the receiver node not able to forward the information to the next node due to not sufficient harvested energy. It can reduce network performance. Here, we propose a new SWIPT mechanism called as hybrid SWIPT (H-SWIPT) to enhance the harvesting energy at which the receiver node not only depends upon the previous node's RF signal but also depends on the neighbor node's RF signal, sink broadcast energy, and co-channel interference. Furthermore, to minimize the total energy consumption of the path a new routing metric is introduced. Based on this, it will select the minimized energy cost path from source to destination. The network performance is evaluated in terms of energy cost and aggregative energy cost and compared with existing schemes: information transmission (IT) & power splitting protocol based SWIPT (SWIPT-PS). From the results, for varying node count, the average energy cost is observed as 5.9mW, 5.433mW, and 4.7mW for IT, SWIPT-PS &H-SWIPT respectively.

Keywords: IoT, SWIPT, Power splitting, Time switching, Co-channel interference, Energy consumption.

1. Introduction

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 (example: sensors) 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]. The viable solution for the above problem is to transfer the power wirelessly or SWIPT [6-8]. SWIPT serves as a basic building block for self-sustained communication networks and the key to unlock the capability of IoT networks. SWIPT consists of two basic receiver architectures. They are time switching (TS) and power splitting (PS) architectures. Maintaining an optimal splitting ratio using TS and PS protocols is one of the major issues. Time switching or power splitting ratio provides the decision that how much percentage of power is required for ID & how much percentage of power is required for EH from the total received power (RF signal power). This causes an imbalance in the network and impacts overall system performance. Hence, to improve overall system performance, there is a need to develop a new technique in SWIPT which allocates the energy and information properly.

Energy harvesting in SWIPT is one of the major concentrated areas for researchers to improve the IoT network performance. Most of the researchers have used either PS or TS protocol to improve the system performance. Recently S. He et al. [9] proposed SWIPT based route selection mechanism for multi-hop energy-constrained wireless network to reduce energy consumption. Initially, they formulated a resource allocation problem for a link to forward the RF signal which consists of information and energy and it is always reliant on the following-hop node. Later, they proposed a unique routing metric to find out the route with minimum energy cost. In [10], sethu Lakshmi et. al. 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 well in respect of EH than the TS protocol for the higher value of SNR whereas TS protocol executes well in respect of data rate than the PS protocol for the lower value of SNR. From [26-28], authors developed a hybrid model which improvises the sensor network performance in terms of throughput, energy efficiency, data rate (throughput) & EH capacity. However, in all of the above methods, the previous node's RF signal is used to harvest the energy by the receiver node. But it is not enough to forward the data successfully to the next node or destination because of the following reasons: continuous sensing, computation, and data transmission of each sensor in the network, presence of different channels or radio mediums between the sensors, and uneven distances between the sensors. So, there is a need to improve the energy harvesting capacity of each node in the network.

In the conventional SWIPT technique energy harvesting only depends on the previous node’s RF signal but here we considered the neighbor node's RF signal and it is an effective source of energy to increase the EH capacity. This work proposes a new SWIPT method that uses a hybrid protocol (combination of TS and PS protocol) in each sensor node to improve the conventional energy harvesting capacity. Here we aim to minimize the end-to-end energy path cost using routing metric and increase the energy harvesting capacity as an additive feature to improve the lifetime of a network. In this architecture, energy harvesting is done by each sensor in three ways: i) from sink broadcast energy in time switching mode ii) from its desired receiver node’s RF signal in information receiving mode during power splitting mode iii) from any undesired neighboring nodes RF signal which do not participate in the transmission or reception of information during power splitting mode. Due to this, the network lifetime will be improved in an IoT. The major contributions of this work are summarized below.

i) To improve the lifetime of an IoT network, this work introduces a new architecture called as hybrid SWIPT (H-SWIPT) that considers PS and TS protocols simultaneously.

ii) 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.

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

iv) 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 below sections. The literature related to this work is discussed in section 2, the network model and proposed H-SWIPT technique is illustrated in section 3, energy-constrained route selection mechanism is elaborated in section 4. Simulation results of this work and their analysis are presented in section 5. Finally, the conclusion & future scope are given in section 6.

2. Related work

In this section, Literature related to SWIPT for energy harvesting and routing in multi-hop IoT networks is reviewed. SWIPT is one of the emerging techniques to serve the energy needs of IoT networks. In [11-13], the detailed survey on relaying in IoT and SWIPT techniques are reviewed. In [9], the authors 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. The energy cost and aggregative energy cost of IT link (without SWIPT) is compared with SWIPT-PS link in terms of barrier rate, minimum energy required for forwarding, and number of nodes. But in SWIPT- PS, if the interference increases, the transmitted signal power gradually reduces. This received weak signal power is again divided into two halves for simultaneous ID & EH operations. The amount of energy harvested by the EH circuit is not sufficient for the transmission of information to the next node or destination. In [14], to minimize the circuit complexity and power consumption, the authors designed a receiver circuit to process the SWIPT signals for information decoding. It has been achieved initially by rectification of signal & then dividing the signal for information and energy allocation. They have not focused much on increasing energy harvesting capacity. Jie tang et. al. [15] proposed an energy efficiency optimization problem for SWIPT multi-input multi-output broadcast channel using TS receiver design. To increase the network transmission power, the authors tried to minimize the amount of energy harvested per user. The authors mainly concentrated on past node RF signal to harvest the energy and not concentrated on remaining nodes which are not participated in the transmission or reception.

Songtao guo et. al. [16] proposed a problem in clustered wireless sensor networks for SWIPT. Here optimization of energy efficiency has been done based on the transmit power, value of PS ratio, 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. While doing this process, the head node of the cluster loses its energy & 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 does not 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. In [17], the authors proposed a multi-objective optimization problem for cognitive networks to maximize network efficiency and secure communication based on SWIPT technique. They divided the optimization problem into three objectives: increasing energy harvesting efficiency, transmission power minimization, and interference-power leakage to transmit-power ratio minimization. They have been used only secondary receivers to harvest the energy and not concentrated on idle primary receivers and only focused on the need for secure communication.

Yifan hu et. al [18] suggested a novel EH technique based on DTS (discrete-time-switch) & PS protocols to increase the average energy transfer rate and information rate. They focused on energy transfer rate but not on energy harvesting capacity. Several studies for SWIPT [19, 20] show that even though the links related to the interference are harmful to decoding the information but these links can be helpful to harvest the energy in multi-user systems. C. Psomas et. al. [21] evaluated the impact of successive interference cancellation (SIC) on the SWIPT performance based on PS technique by considering a bipolar ad-hoc network. The main moto of SIC is that some signals related to interference may be strong enough to decode the information instead of removing from aggregated received signal. It boosts the performance of a network. Their results have been shown notable energy gains under certain scenarios. In [22], the authors evaluated the downlink SWIPT-NOMA system performance. Here, they have used the power splitting technique to derive the expression for the signal to interference noise ratio (SINR) and outage probability for each near and far end-user where the user near 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. In [23], authors formulated a novel optimization problem that minimizes the total system’s energy consumption subject to the constraints like transmitting power and data transmission rate, CPU frequency, offloading weight factors, and energy harvesting weight factor. They compared simulation results with two benchmark algorithms but not considered the neighbor nodes RF signal. In [24], the authors proposed a heuristic energy-efficient cooperative SWIPT routing algorithm to find a transmission path with the maximum energy efficiency based on the SWIPT-PS technique for 5G systems. They have been set minimum path energy efficiency cost as the optimization object to find maximum energy efficiency. Moreover, the harvesting energy depends only on the cluster head node RF signal. They have not considered the cluster member nodes energy which is neither participated in transmission nor reception.

In [25], the authors proposed multi-hop MIMO relaying based on SWIPT by incorporating TS and PS protocols. The current relay depends on the immediate preceding relay node to harvest the energy using the SWIPT technique. 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 not near the source. So as the distance from the source node increases, harvesting energy decreases. This will lag the network performance. Furthermore from [26-28], observations have shown that hybrid protocols are more effective than traditional protocols like PS or TS protocols to improve the wireless sensor network performance. By reviewing all of the above existing methods, in SWIPT for multi-hop IoT networks to

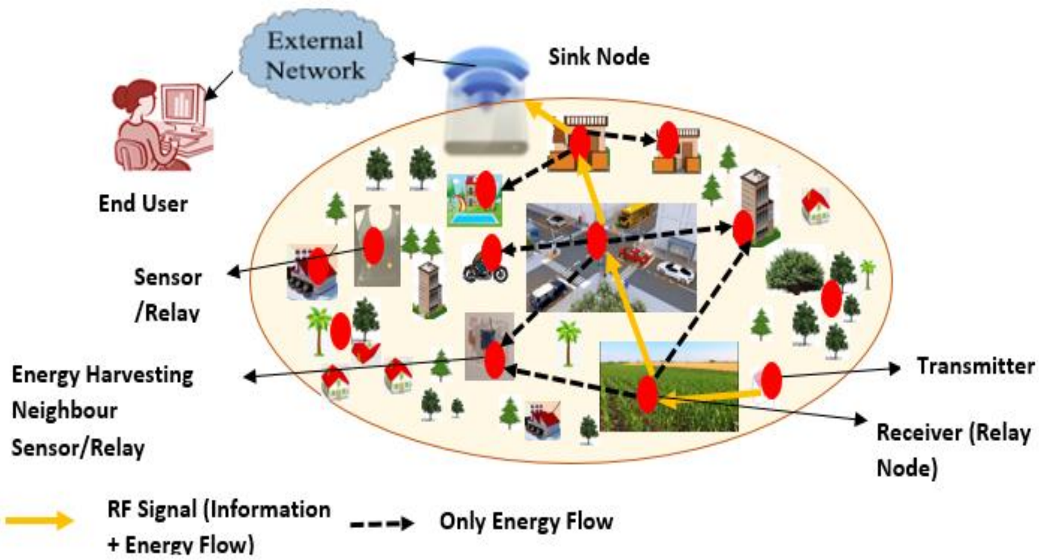

Figure. 1 Network model

harvest the energy, the receiver node can only depend on transmitter node RF signal. They have not concentrated on remaining nodes or neighbor nodes RF signal. The neighbor nodes are neither participating in transmission nor reception which are remain idle in the network. It is a valid source of energy to improve the capacity of energy harvesting. Here, we are not only concentrated on improving energy harvesting capacity but also on efficient data transmission. It is achieved by using an efficient routing mechanism that will select the minimum energy consumed path that leads to improvement in the network lifetime.

3. Proposed method

This section describes the network model and proposed H-SWIPT

3.1 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 [29]. Here assumed some amount of energy was given to all the sensor nodes initially. Each sensor node has operated in three modes. They are information transmission mode (IT), information reception mode (IR), energy harvesting mode (EH), 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 split 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 like energy harvesting in only IR mode.

3.2 Network model

This paper considers an architecture for a multi-hop wireless IoT network as shown in Fig. 1 with N number of 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 & 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= (V, E) consists 'V' number of vertices or sensor nodes & 'E' number of edges or links. A directed link between any two nodes (assume i, j) is valid only when the Euclidean distance (d_{ij}) between them is less than or equal to the communication range

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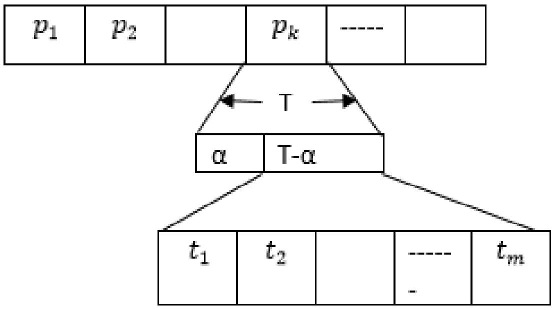

Figure. 2 Structure of time slot (T)

(r) i.e. $d_{ij} \leq r$. 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] with imperfect channel state information (CSI) [31] and the receiver's antenna noise is additive white Gaussian noise (AWGN).

3.3 H-SWIPT

The sink node gathers information in the collection period $(p_1, p_2, \dots p_k \dots)$ from all the sensors which are 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 'α' is for energy broadcasting by the sink node and another time duration (T- α) is for information transmission. Furthermore, (T- α) time duration divided equally into 'm' number of information transmission time slots among N sensors having equal time interval t ($|t_1| = |t_2| \dots\dots = |t_m| = t$). Here maximum 'm' number of sensor nodes information transmits simultaneously when it holds α+mt<=T inequality as illustrated in the Fig. 2

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 [32] during practical operations in the receiving sensor, the 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. 3. Here, the power loss and noise produced by TS and PS units at the time of signal processing were 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. 3. 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 & 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. Working steps are described below.

1. The sink node broadcasts energy in 'α' time duration as shown with dotted lines in Fig. 3. In this duration, all sensors in the network harvest energy at a time from the sink node.
2. The following operations are done in t^{th} time interval independently (not at a time) and it is illustrated in the Fig. 3

a. When the time switcher shifted to IT mode, as shown in Fig. 3 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 neighbour nodes (undesired receiver nodes) receives only energy indicated with a blue dotted arrow.

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

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

According to our proposed H-SWIPT, 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 it is given by

$$E_T^{eh} = E_{max} + E_{IN} + E_{SN} + E_{NN} \qquad (1)$$

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

$$E_{max} = \sum_{i=1}^{s} P_{ij} \varepsilon \eta_{ij} \, \rho_{ij}^{E} h_{ij} t, \;\; s \epsilon N \qquad (2)$$

Where s is a collection of transmitting sensor nodes where node j is treated as a relay, P_{ij} is transmitting power, ε is energy harvesting coefficient (0< ε <1), η_{ij} is energy conversion coefficient (0<η_{ij}<1), ρ_{ij}^{E} is power splitting ratio for EH, and h_{ij} is channel power gain coefficient.

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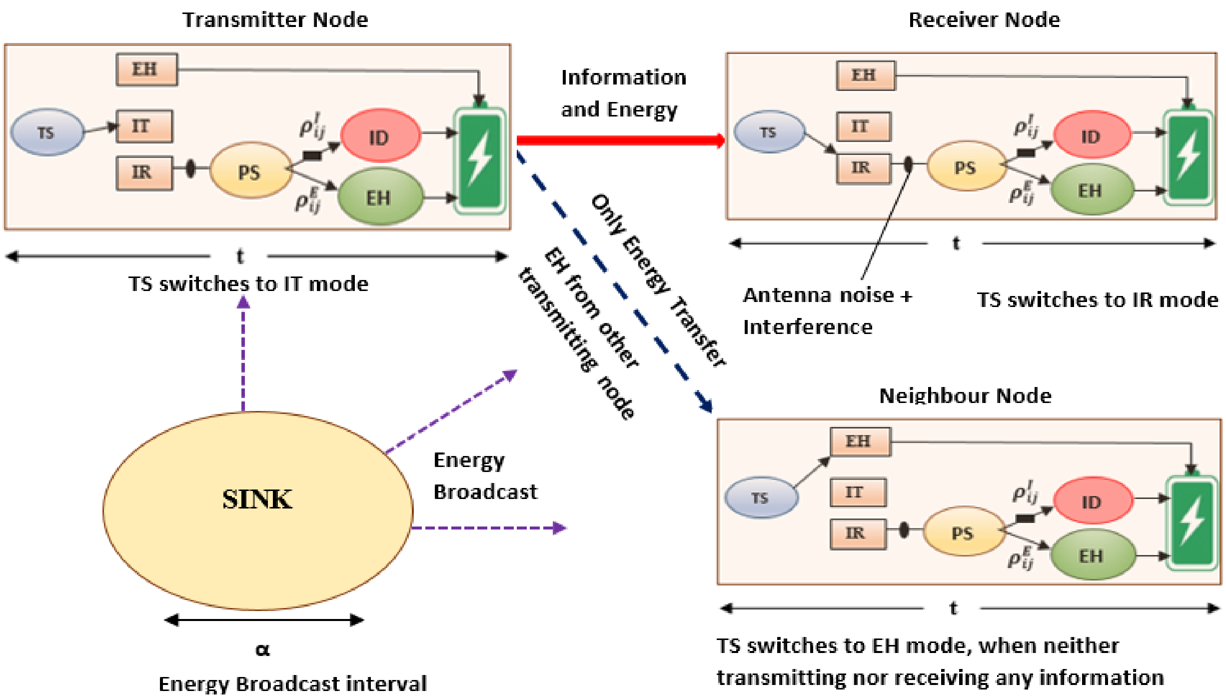

Figure. 3 Architecture of H-SWIPT

2. E_{IN}: 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

$$E_{IN} = \sum_{i=1}^{s}(\sigma_{I,ij}^2 + \sigma_{ij}^2)\, \eta_{ij}\rho_{ij}^{E}t \tag{3}$$

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

3. E_{SN}: In time interval α, the amount of energy harvested by receiver node j from sink broadcasting power P_{sb} is given by

$$E_{SN} = P_{sb}\varepsilon\eta_{ij}h_{ij}\alpha \tag{4}$$

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

$$E_{NN} = \sum_{i=1}^{n} P_{ij}\varepsilon\eta_{ij}\, h_{ij}\mathrm{t}(1 - b_{ij}) \quad ,, n\epsilon N \tag{5}$$

Here, 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.

4. Energy-constrained route selection

Energy-constrained 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. In energy-constrained multi-hop IoT networks 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 & power. Here, the H-SWIPT link is used instead of the conventional SWIPT (SWIPT-PS) link to enhance the lifetime of the network. Let us assume the transmitting node i sends information through the link l_{ij} with IT to the receiver node j. We consider the E_C of the link l_{ij} with IT is $E_{C(i,j)}^{IT}$ & it is equivalent to the power P_{ij}.

$$E_{C(i,j)}^{IT} = P_{ij} \tag{6}$$

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) (γ_{ij}) of the received signal should be greater than the minimum signal to noise ratio requirement γ_{min}. So,

$$\gamma_{ij} \geq \gamma_{min} \quad (7)$$

So, the minimum $E_{C(i,j)}^{IT}$ is given by

$$E_{C(i,j)}^{IT} \geq ({\sigma_{ij}}^2 + {\sigma_C}^2)\, \gamma_{min}/|h_{ij}|^2 \quad (8)$$

Where ${\sigma_{ij}}^2$ is power of antenna noise from node i to node j and ${\sigma_C}^2$ is power of signal conversion noise from node i to node j. 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 $E_{C(i,j)}^{H-SWIPT}$ and it is given by

$$E_{C(i,j)}^{H-SWIPT} = P_{ij} - E_T^{eh} \quad (9)$$

Further, the receiver node j tries to forward the information to the next-hop node. Before going to forward the information to the next node, it will verify the receiver node's energy harvesting power requirement Preq_j. To forward the information from the receiver node to the next-hop node successfully, the following condition should be satisfied.

$$E_T^{eh} \geq \mathrm{Preq}_j \quad (10)$$

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

$$\mathrm{Preq}_j = P_{jk} \quad s.t.\, a_{jk} = 1 \quad (11)$$

In SWIPT, the amount of information transmission or energy harvesting is decided based on PS & TS ratios. Hence, the above equation is reformulated as

$$E_{C(i,j)}^{H-SWIPT} = P_{ij} - \rho_{ij}^E E_T^{eh} \quad (12)$$

Using the above equation, 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 & j otherwise based on the value of splitting ratio both information transmission and energy harvesting takes 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

$$E_{Total(s,d)} = \sum_{l_{ij} \epsilon path_{sd}} E_{C(i,j)}^{H-SWIPT} \quad (13)$$

Let us assume one binary variable a_{ij}, if it is equal to one, the link between the nodes i & 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

$$f(x) = \min_{\rho,P} \sum_{l_{ij}} a_{ij}(P_{ij} - \rho_{ij}^E E_T^{eh}) \quad (14)$$

s.t.

$\gamma_{ij} \geq \gamma_{min}, \quad \forall i,j \quad E_T^{eh} \geq \mathrm{Preq}_j \quad \forall i,j$

$\mathrm{Preq}_j = P_{jk}\ if\ a_{jk} = 1\ P_{ij} \epsilon [0, P_{max}]\ \forall i,j,$
$\rho_{ij}^E \epsilon\, [0,1]$, $\rho_{ij}^I \epsilon\, [0,1]$ and $\rho_{ij} = \rho_{ij}^I + \rho_{ij}^E \leq 1$,
$a_{ij} \epsilon \{0,1\}, \forall i,j$, α>0, T>0, α+mt<=T, i,jϵ [1……N]

5. Simulation results and analysis

In this section, simulation experiments are executed to evaluate the performance of the proposed H-SWIPT.

5.1 Simulation scenario

In our simulation, we consider a random number of nodes varying from 20 to 70, and they are located over the area of 100mX100m. 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 100mw. We set the minimum harvest energy to be 10% of P_{max} & the minimum energy requirement for forwarding (Er_{min}) the information is 0.4. We consider that all nodes in the network have the same noise parameters. The remaining parameters used for simulation is listed in Table 1.

Nodes cannot communicate with each other even though they are in transmission range because of physical barriers. These physical barriers affect the network performance. 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. To evaluate the performance of this work, we compared the proposed H-SWIPT

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Table 1. List of parameters used for simulation

parameter	value
$\|h_{ij}\|^2$	1
γ_{min}	20dB
${\sigma_{ij}}^2$	-50dBm
${\sigma_C}^2$	-70dBm
ε	0.65
T	30s
t	1s
m	25
s	5
η_{ij}	0.8
$\sigma_{I,ij}^2$	10dBm
br	30%
n	5

technique with IT [9] & SWIPT-PS [24]. For both IT and SWIPT-PS techniques, we apply an energy-efficient routing method to find the minimum energy cost flow of the path. We use two metrics: energy cost and aggregative energy cost to evaluate the performance. The total energy consumption of a route from source to destination is calculated using energy cost. Aggregative energy cost is the sum of all other nodes energy cost from source to destination. To validate the performance of H-SWIPT, three sets of simulation experiments are executed to observe the effect of barrier rate, the minimum energy required for forwarding, and node density. We set the barrier rate for all simulations as 30%. In the following section, simulation results are presented.

5.2 Simulation results

Fig. 4 (a) shows the energy cost versus the number of nodes. This work considers 20 to 70 nodes to estimate the effect of node density on network performance. If we observed the Fig. 4 (a) when the number of nodes is increasing from 20 to 70 the energy cost of the three routing schemes is decreasing gradually. But when the number of nodes increases from 30 to 60, the energy cost of H-SWIPT starts decreasing more than SWIPT-PS & IT. Hence, H-SWIPT has shown better results compared to SWIPT-PS and IT at higher node density because of the decrease of active nodes to forward the information. As the number of active forwarder nodes decreases the energy available at a particular node is not enough to forward the information to the next-hop node through IT or SWIPT-PS links. In addition to that H-SWIPT based route selection mechanism selects the lesser energy nodes as active forwarder nodes to transfer the data from the source to the destination. From the results, we observed an average improvement in the reduction of energy cost for H-SWIPT with IT and SWIPT-PS is 19.38% and 12.31% respectively.

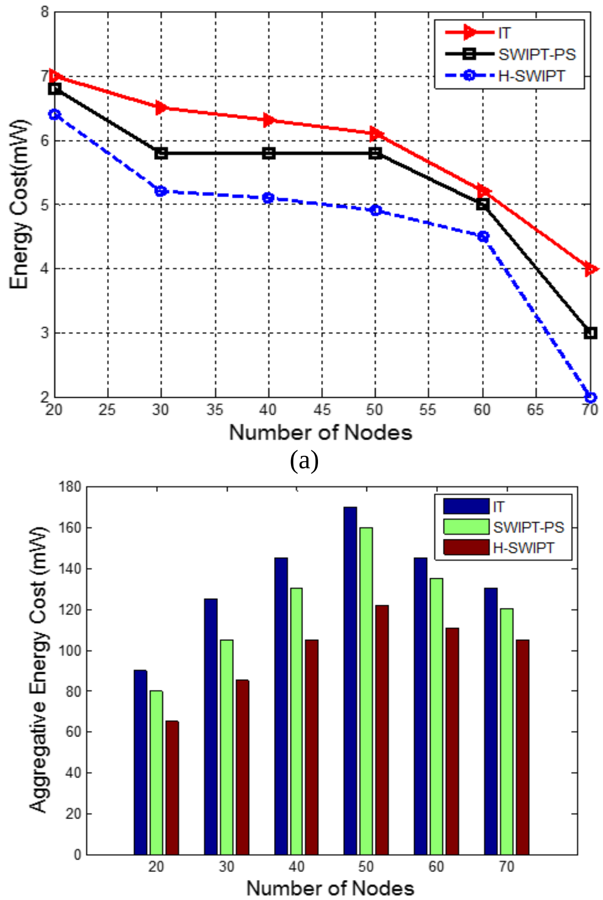

Figure. 4 Effect of node density on: (a) Energy cost and (b) Aggregative energy cost

Fig. 4 (b) shows the aggregative energy cost versus the number of nodes. If we observed the Fig. 4 (b), initially when the node density increases the aggregative energy cost is also increases because it is all nodes' cumulative energy cost. But when the number of nodes increases from 50 to 70, the count of active nodes increases, and the energy cost of each node decreases gradually. It indicates the reduction of aggregative energy cost because it uses lesser energy nodes are the efficient nodes to forward the data from source to the destination. From the results, we observed an average improvement in the reduction of aggregative energy cost for H-SWIPT with IT and SWIPT-PS is 29.29% and 19.65% respectively.

Fig. 5 (a) shows the energy cost versus minimum energy requirement for forwarding Er_{min}. When the residual energy of a node is less than Er_{min} the count of inactive nodes increases. It will impact the

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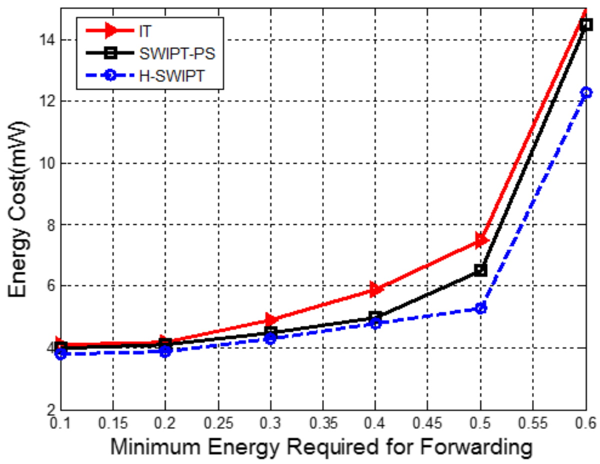
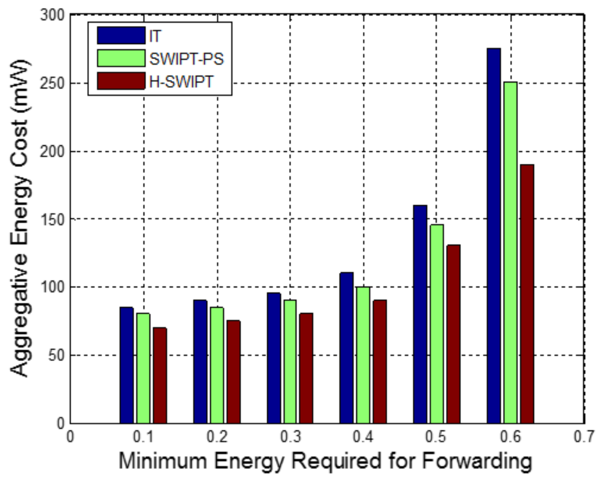
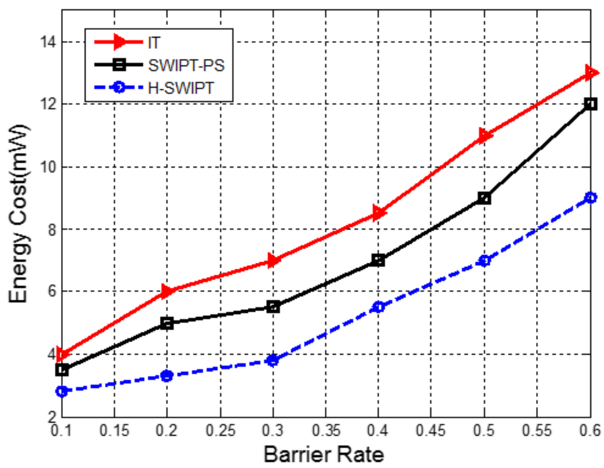


(a)

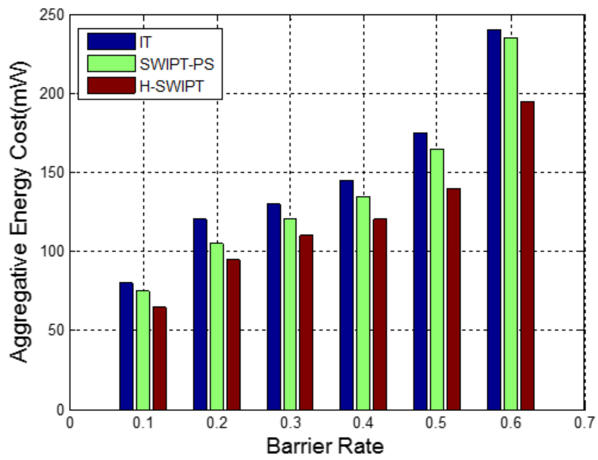


(b)

Figure. 5 Effect of Er_{min} on: (a) Energy cost and (b) Aggregative energy cost



(a)



(b)

Figure. 6 Effect of barrier rate on: (a) Energy cost and (b) Aggregative energy cost

performance of a network. For 30 nodes, we consider the lower value for Er_{min} is 0.1 and the higher value is 0.6. If Er_{min} increases the number of active nodes decreases and energy cost increases as shown in Fig. 5 (a). When the Er_{min} is equal to 0.2, three schemes' energy cost is approximately equal because of the huge availability of active nodes to forward the information. But when it is increasing from 0.2 to 0.6, the energy cost is also increasing because of less availability of active nodes to forward the information. At this point, H-SWIPT has shown good results compared to IT and SWIPT-PS because it considered neighbor nodes' RF signal to harvest the energy in addition to previous nodes RF signal. Also uses inactive nodes or lower energy nodes as the minimum energy cost path to forward the data from source to the destination efficiently to enhance the network performance. From the results, we observed an average improvement in the reduction of energy cost for H-SWIPT with IT and SWIPT-PS is 17.27% and 11.85% respectively. Fig. 5 (b). Shows the aggregative energy cost versus minimum energy requirement for forwarding. As shown in Fig. 5 (b), if Er_{min} increases then the availability of active nodes to forward the data decreases and aggregative energy cost increases. But in the case of H-SWIPT, the aggregative energy cost increases gradually because it uses lower energy nodes as the minimum energy cost path. From the results, we observed an average improvement in the reduction of aggregative energy cost for H-SWIPT with IT and SWIPT-PS is 25.46% and 19.45% respectively.

Fig. 6 (a) and (b) describes the impact of barrier rate (br) of a network on energy cost and aggregative energy cost. To examine the effect of barrier rate on network performance, assume the barrier rate lower value is 0.1 and higher value is 0.6. When the barrier rate increases, the energy cost and aggregative energy cost also increases as shown in Fig. 6 (a) and (b) because of the unavailability of direct links. When br is 0.1, three schemes' energy cost is approximately equal due to more number of 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. When the br is 0.6, the number of direct links between the inactive node and active node decreases because of unavailable SWIPT links. But in H-SWIPT neighbor nodes can help the node to reach the destination. From the results, we observed an average improvement in the reduction of energy cost for H-SWIPT with IT and SWIPT-PS is 35.39% and 24.39% respectively. At the same time, the reduction of aggregative energy cost for H-SWIPT with IT and SWIPT-PS is 17.82% and 13.33% respectively. Hence the H-SWIPT outperforms IT and SWIPT.

6. Conclusion

The energy consumption of the IoT network increases as there exist uninterrupted sensor devices operations and hence the network performance would get impact. 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 developed an energy-efficient hybrid SWIPT based route selection mechanism for multi-hop energy-constrained IoT networks. Unlike the traditional SWIPT-PS, H-SWIPT involves three different sources for energy harvesting; they are sink node, undesired neighbor nodes, and co-channel interference to enhance the energy harvesting capacity. In addition to that to minimize the total energy consumption of the path from source to the destination energy cost metric is used. To evaluate the network performance energy cost and aggregative energy cost are measured in respect of barrier rate, the minimum energy required for information forwarding, and node density. Results of the proposed work are compared with IT and conventional SWIPT-PS techniques and it shows the effectiveness of the proposed method. From the results, an average improvement in the reduction of energy cost for H-SWIPT is observed as 19.38% and 12.31% from IT and SWIPT-PS respectively. For Er_{min}, it is observed as 17.27% and 11.85% from IT and SWIPT-PS respectively. For varying barrier rate, it is observed as 35.39% and 24.39% from IT and SWIPT-PS respectively.

As most of the earlier researchers on energy harvesting through SWIPT mechanism focused over the enhancement of network lifetime but very less effort has been put on the quality of service (QoS). Since QoS is also an important aspect in IoT, further research can be focused in this direction.

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