Multi-source assisted mixed simultaneous wireless information and power transfer for energy efficient routing in IoT networks

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ABSTRACT

Recently, simultaneous wireless information and power transfer (SWIPT) emerged as the best solution for resource-constrained internet of things (IoT) networks. SWIPT ensures the provision of parallel information and power transfer in the network. Under the SWIPT model, many researchers use two well-established protocols: time switching (TS) and power splitting (PS). TS is better than PS when the signal is weak but inserts an extra delay because energy harvesting (EH) and information decoding (ID) happened two different times. However, PS protocol performs poorly in hard situations with low signal strength even if it conducts EH and ID simultaneously. Hence, this paper proposed a new model called mixed-SWIPT (MSWIPT) which combines TS and PS protocols in an intuitive manner. Further, this work proposes a multi-source EH mechanism in which the receiving node harvests energy from multiple sources which is different from single source, i.e., desired node's radio frequency (RF) signal. The multiple sources include non-participated Neighbor Node's RF signal, sink node and co-channel interference and noise. Under the routing, the node selection is formulated as maximum link capacity problems and solved through several constraints. Extensive simulations on proposed model prove the superiority in terms of EH and energy efficiency from the state-of-the-art methods.

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1. INTRODUCTION

Recently, internet of things (IoT) has gained huge research interest due to its widespread applications in various fields like smart healthcare, smart city, and smart agriculture. IoT technology connects numerous heterogeneous devices to the internet [1]-[3]. Due to this nature of heterogeneity, it has gained popularity in various applications [4], [5]. The nodes in IoT networks monitor critical parameters and forward the processed data directly to the sink node. Such kind of transmission shows notable impact on node's energy [6]. So, maintaining sufficient amount of energy at each node in the context of IoT applications is a promising research area [7]. In this aspect, multi-hop data transmission technique emerged as a promising solution where the nodes' energy is effectively utilized. Multi-hop transmission is executed by the cooperation of neighbour nodes in the network. But it leads to higher data transmission load when the number of connected devices for each node increases. Such kind of connectivity results in quick energy depletion of IoT nodes those are densely connected with other nodes in the network results in an energy holes problem in the network. So, to ensure a better support in multi-hop communication, each node must maintain an adequate amount of energy. Towards such intention, recently some researchers suggested energy harvesting (EH) is one of the promising solutions [8].

There are many sources to harvest the energy from the environment such as wind, thermal noise, vibrations, and radio frequency (RF) signals. The most notable energy source used by IoT nodes for not only EH but also information transmission (IT) is RF signal. In the context of RF based EH, simultaneous wireless information and power transfer (SWIPT) became one of the emerging techniques where EH and information decoding (ID) is done simultaneously [9]. In conventional wireless power transfer (WPT), the RF signal is used only for EH whereas in SWIPT it is used for EH as well as for ID. To execute the above functions (i.e., ID and EH), SWIPT uses a receiver circuit where EH and ID are separated from each other. Basically, there are two types of SWIPT receiver architectures namely times switching (TS) and power splitting (PS). In TS, the same RF signal is used for both EH and ID in two different time intervals. On the other hand, in PS architecture, RF signal is divided into two parts; one part is used for EH and the other part is used for ID. So, the partitioning of RF signal is accomplished based on time switching ratio in TS and PS ratio in PS. These two ratios show a significant impact on the SWIPT architecture. For example, consider PS protocol, the information rate becomes less when most part of RF signal is used for EH. On the other hand, the EH will get affected if most part of the RF signal is spent for ID. In summary, a non-uniform partitioning of RF signal [10]-[27] based on TS and PS ratios has huge impact on the energy consumption of network which directly impact on the network lifetime. Hence, there is a need to design a hybrid SWIPT architecture which overcomes the individual problems of TS and PS architectures and improves the network lifetime by utilizing energy efficiently.

Most of the past researchers employed either TS SWIPT protocol or PS SWIPT protocol for maximizing energy efficiency along with data rate improvisation [10]-[19]. Recently, some authors shifted their thoughts over hybrid architectures and introduced new SWIPT models [20]-[27]. But all of them referred to only one source (i.e., the RF signal of past-hop node) [10]-[27] for EH but not concentrated on the alternative valid EH sources. If these sources are utilized efficiently for EH in the network, then each node can get sufficient amount of energy. In such regard, this work introduced a new SWIPT architecture associated with multiple sources for EH. Here we outline the overall contributions:

a. To maintain adequate energy at every node in IoT network, this work recommends compound sources for EH. Unlike most of the existing methods which considers only one source (the RF signal of past-hop node) for EH at node, this method considers four sources namely: i) non-participated neighbor node's RF signal, ii) sink node, iii) co-channel interference and noise, and iv) designed node's RF signal.
b. To ensure better network performance, this work proposed a new SWIPT architecture by combining TS and PS protocols. The proposed work alters the TS and PS ratios to integrate the PS and TS protocols into single architecture.

The rest of the paper is organized as follows: section 2 explores the literature survey particulars. Section 3 explores the complete particulars of proposed hybrid SWIPT architecture and compound source assisted EH mechanism. Section 4 explodes the experimental investigations on proposed methodology and section 5 concludes the work.

2. RELATED WORK

Due to the novelty of EH concept in wireless networks, different network related researchers were proposed different methods. To prolong the lifetime of the network, He *et al*. [10] introduced a SWIPT based multi-hop energy constrained network. They considered the RF signal of only past-hop node for EH and proposed a multi-hop routing where the next-hop node is selected based on its energy consumption. In an IoT network, one node can act as energy and information transmitter for more than one neighbor node. In such constraints, the receiver node won't harvest sufficient amount to forward the data towards the destination node because it results in huge energy consumption which directly impacts the performance of IoT network.

Ashraf *et al*. [11] suggested SWIPT assisted cooperative relaying technique for low powered IoT networks to perform data and energy transmission simultaneously. They considered two different scenarios for performance assessment, they are; i) EH relay and EH-IoT device and ii) EH relay and non-EH IoT device. They considered decode and forward relay and employed an adaptive PS mechanism under various channel conditions to harvest the energy and to locate the relay. Chen *et al*. [12] proposed a framework for wireless sensor networks (WSN)-assisted IoT network where the network's energy consumption is computed in terms of various parameters like data transmission rate, transmitting power, EH weight factor, and offloading weight factors. However, they didn't suggest an alternate solution if the harvested energy is not enough when the energy consumption increases.

To enhance the battery life of IoT network, Wang *et al*. [13] proposed simultaneous wireless information and power transfer power splitting (SWIPT-PS) based cooperative relay scheme with direct link. To achieve maximum sum-rate, the authors considered per-antenna power constraint for each direct link and computed energy from the available past-hop node only. In summary, they concentrated only on achieving the maximum data rate but not on EH which directly impacts the network lifetime. Imani *et al*. [14] aimed at the improvisation of network lifetime in WSN by incorporating SWIPT mechanism. In addition to the past node's RF signal, they suggested harvesting the energy by considering the quality of fading channel. In addition, a relay selection mechanism is also introduced based on the available harvested energy.

To provide sufficient energy for ground IoT devices, Huang *et al*. [15] suggested a new SWIPT assisted EH mechanism for IoT based unmanned aerial vehicle (UAV). The authors investigated trajectory design and power allocation of the UAV to provide a well-defined infrastructure for IoT devices. They maximized the minimum energy harvested among multiple ground IoT devices that are located with unequal distances. However, the survival of every IoT device is dependent only on the harvested energy. Such dependency impacts the network performance when the harvested energy is less because there is no alternate EH source.

Rauniyar *et al*. [16] suggested SWIPT time splitting (SWIPT-TS) based capacity enhancement scheme for IoT systems over Rayleigh fading channels. Authors measured total harvested energy over various channel conditions and used it for capacity enhancement. Only a single source is used for EH and it is not sufficient for data forwarding at the weak transmitted RF signal. Khan *et al*. [17] proposed SWIPT-TS technique called as energy efficient peer selection and time switching ratio allocation (EPS-TRA) algorithm. They used TS protocol for ID and EH simultaneously which in turn provides uninterrupted communication for resource constrained IoT devices. Next, the RF signal of past-hop node is utilized for EH. However, it is not enough when the distance between the devices is increased.

Tang *et al*. [18] suggested a solution for energy efficiency optimization problem for non-orthogonal multiple access (NOMA) system in IoT networks. They suggested harvesting the energy from fixed energy sources and the amount of harvested energy varies with TS ratio. In addition, k number of terminals shares the transmitted RF signal. In such a scenario, if transmitted RF signal is weak then the harvested energy is not enough to handle all terminals. To improve the SWIPT network performance, Hu *et al*. [19] introduced an EH technique using directional transmitters. The authors suggested harvesting energy from the RF signal of past-hop node, and it is transferred to specific receivers through double discrete-time-switch (D-DTS) protocol. If the transmission medium is lossy, then this technique shows less performance in terms of energy and power transfer.

Jiang *et al*. [20] investigated the transmit power of SWIPT-IoT networks using nonlinear EH model under coexisting time-switching users (TSU) and power-splitting users (PSU). Authors formulated a transmit power minimization problem and delivered a solution by optimizing the constraints such as PS, TS ratios, and hybrid-access point (H-AP) beam form vectors. They also investigated the quantity of harvested energy by considering linear and non-linear EH models. Based on the results, we observed that as the interference among the TSUs and PSUs increases, the harvested energy gets decreased.

Batool *et al*. [21] proposed SWIPT assisted hybrid protocol to enhance the quality of service (QoS) of IoT networks. End-to-end outage probability and average harvested energy (AHE) metrics are considered to compute the overall QoS of the network. Based on the proposed hybrid protocol, authors investigated the impact of PS and TS ratios on the AHE and end-to-end outage probability. However, they harvested the energy only from desired past-hop node's RF signal and they were not considered the remaining nodes' RF signal which are neither participate in transmission nor in reception.

Gautam *et al*. [22] proposed a solution for the optimization problem by considering optimization parameters such as harvested energy, throughput, and transmit power of the network. In this regard, authors used hybrid active-and-passive relaying model that considers TS and PS receiver architectures. They investigated the performance of the network under linear and non-linear EH models by varying transmit power. However, as the transmit power increases the harvested energy increases and vice versa.

Rahman and Kader [23] proposed a new RF-EH mechanism with an aim of improvising the EH capacity of cooperative multi-relay IoT network. Energy is harvested at the destination node based on the cooperation between the source and relay nodes. They harvested the energy in two phases, they are: i) each relay in the network harvests energy from the transmitted RF signal from the source and ii) the destination node harvests the energy from the relay node and the source node.

Singh *et al*. [24] introduced two new relaying protocol based on SWIPT; they are adaptive power splitting (APS) and adaptive time switching (ATS) protocols. The PS and TS ratios are optimized dynamically in the proposed two protocols according to their channel states among the relays. The effective transmission rate and outage probability are computed based on the harvested energy. However, the amount of harvested energy is not enough when the channel is deeply faded.

Singh *et al*. [25] proposed SWIPT based network-aware positioning of RF-energy transmitter technique for energy efficient IoT network. In this regard, authors considered various parameters such as data routing information, energy-hole information, and node-connectivity information. In addition, different RF propagation models are analyzed to enhance the EH capacity. They combined more than two propagation models to predict the signal strengths there by predicting the available residual energy for EH. Tang *et al*. [26]

proposed a solution for energy efficiency optimization problem for SWIPT. The authors used SWIPT-TS receiver architecture to measure energy efficiency. They maximized energy efficiency by considering the constraints such as maximum transmitting power and minimum harvested energy per user. However, they did not concentrate on the amount of harvested energy.

Fan *et al*. [27] introduced a Hybrid SWIPT with decode and forward relay in multi-hop IoT network. They employed both TS and PS protocols for EH in two strategies, they are: i) uniform TS and PS ratios and ii) varying TS and PS ratios. They employed only one source for EH, i.e., RF signal past-hop node. Pavani *et al*. [28] introduced a new SWIPT mechanism called hybrid SWIPT (H-SWIPT) 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. But they did not focus on how much energy was harvested. Considering the energy consumption of IoT-based WSN nodes, Zeb *et al*. [29] proposed a simple energy-efficient routing technique to consume less energy. The protocol incorporates efficient link selection based on the closest angle to the destination node and is divided into two main parts: distributed neighbor discovery and routing processes. By incorporating EH techniques, the proposed model aims to improve network longevity.

Tavana *et al*. [30] assume that the IoT devices periodically harvest energy from multiple surrounding base stations (BSs) and use the harvested energy to take sensor measurements and transmit related data packets. They propose an approximate method to analyze the feasibility of this approach in terms of which measurement rates can be supported. They assume a poisson point process for the locations of the BSs. Mathematical expressions are derived for the coverage probability (i.e., the probability that an IoT device harvests enough energy to operate at a given measurement rate) and the required BS site density in the presence of channel uncertainties, blockage, and harvesting nonlinearities. Gamma distribution parameters are derived to approximate the distribution of the harvested power.

Hammoud *et al*. [31] proposed a joint opportunistic EH and communication system (JOE-HC) using visible light communication (VLC). This system can perform simultaneous light information and power transfer (SLIPT) to support battery-less photovoltaic (PV)-equipped IoT devices. The spatial signal to interference plus noise ratio (SINR) is optimized using the spatial-time division switching (S-TDS) scheduling approach in the JOE-HC. They added a time delay guard to eliminate the signal interference caused by the switching impairments of the light transmitters, where the light-emitting-diode (LED) serves for illumination and communication purposes. Table 1 shows the limitations of existing mechanisms. Problem statement: all existing methods have been concentrated only on EH but not on IT rate. Moreover, only a single energy source i.e., past-hop node's energy is used to harvest the energy, and it is not enough when one node acts as information and energy transmitter for multiple nodes in the network. In such cases, the proposed mechanism uses multiple alternative energy sources to harvest the energy using efficient hybrid SWIPT architecture.

Table 1. Limitations of existing mechanisms

S. No.	Reference	Method	Remarks
1	[10]	SWIPT-PS	Past-hop node's energy is used to harvest the energy. Energy consumption increases when the number of nodes increases.
2	[13]	SWIPT-PS	Considered the power constraint to maximize the sum-rate. Concentrated only on maximizing the data rate but not EH.
3	[16]	SWIPT-TS	Harvested energy at various channel conditions but used only single source. Not concentrated on data transmission.
4	[19]	SWIPT-TS	D-DTS protocol is used for EH and IT. Energy and IT rate decreases when transmitting media is lossy.
5	[22]	Hybrid SWIPT	Linear and non-linear energy models are used to harvest the energy. Harvesting energy mostly depends on transmitted power.
6	[26]	SWIPT-TS	Maximize energy efficiency by considering constraints such as maximum transmit power and minimum harvested energy per user. Not concentrated on amount of harvesting energy.
7	[27]	Hybrid SWIPT	They considered two cases such as uniform TS and PS ratios and varying TS and PS ratios. Only single source is used to harvest the energy.

3. PROPOSED MIXED SWIPT BASED ROUTING MECHANISM

In this section, it is explained the results of research and at the same time is given the comprehensive discussion. Results can be presented in figures, graphs, tables and others that make the reader understand easily [14], [15]. The discussion can be made in several sub-sections.

3.1. Overview

This section explores the details of our proposed approach. Under this approach, we modeled a new SWIPT architecture named mixed SWIPT (M-SWIPT) which combined both TS and PS protocols in an efficient manner. According to the proposed architecture, the entire functioning is accomplished in two phases, EH phase and simultaneous data transmission and EH phase. These two phases consider time interval as a reference parameter to get executed. At first phase, all the nodes present in EH mode and harvest the energy from the signal broadcasted from sink node. In the next phase, the node present in either Transmission or receiving mode and executes data transmission process along with EH if required. In addition, this work proposed a compound source-based EH concept in which the nodes harvest sufficient amount of energy from multiple sources. Unlike the previous method which suggested only past-hop node's RF signal for EH, this work proposes multiple sources (co-channel interference and noise, unintended neighbor nodes' RF signal and designed node's RF signal) for EH. The complete details of system model, receiver models, M-SWIPT and its compound sources are demonstrated in the following subsections.

3.2. System model

This work considers a multi-hop IoT network which consists of one sink node and N number of sensor nodes (SN). Each SN is able to sense, compute, and transmit through single antenna and it acts as both energy and information transmitter. Here, the sink node acts as central controller of the network, and it handles all the signaling and routing related issues. The sink node is used to gather the information from all the SNs as well as broadcasting the energy to them as it is shown in Figure 1. This network resembles the nature of a directed graph $G = (n, l)$, where n represents number of SNs, and l represents number of links. There exists a direct link between the two nodes (assume i and j) $(i, j) \in l$ when they are separated with a distance less than or equal to the sensor transmission range i.e., $d_{ij} \leq r$. The sensor transmission range varies with respect to transmission power. Here, we assume quasi-static block-fading channel model between the transmitter and receiver with Rayleigh distribution. Further, imperfect channel state information (CSI) and additive white Gaussian noise (AWGN) are considered.

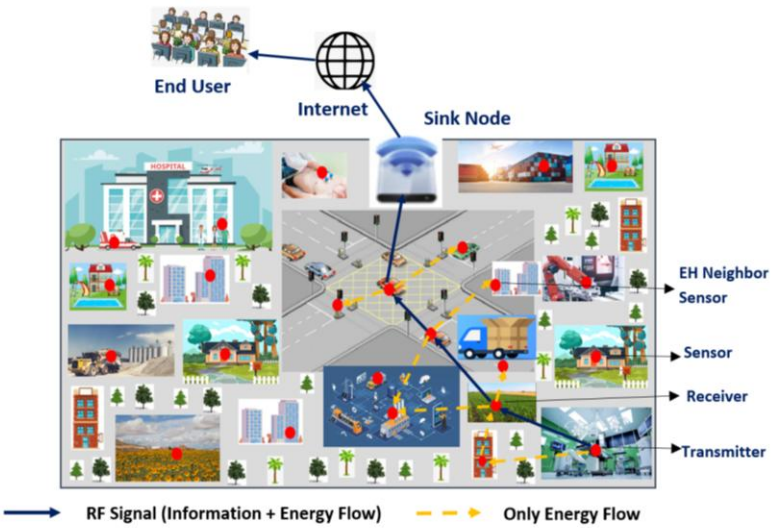

Figure 1. Basic network model

3.3. Receiver models

In this section, the basic receiver models such as IT, SWIPT-PS are discussed. IT receiver consists of only ID unit whereas SWIPT-PS receiver consist of both ID and EH unit.

3.3.1. Information transmission receiver

Generally, most wireless communication networks use IT mode of transmission to transmit the information from transmitter node to receiver node. The basic receiver architecture of IT is shown in Figure 2, where the complete received RF signal is used by signal processing unit. Later, it is forwarded to the information decoder (ID) unit. Here, we assume AWGN with zero mean and $\sigma^2_{A,ij}$ variance. Then the received RF signal $y(t)$ [28] is given by (1):

$$y(t) = \sqrt{P_{ij}} h_{ij} x(t) + \sum_{I=I_1}^{I_m} \sqrt{P_{Ij}}\, h_{Ij} x(t) + n_{A,ij}(t) \quad (1)$$

where, P_{ij} is the transmitting power, $n_{A,ij}(t)$ is the antenna noise, I is the set of neighbor interfering signals, P_{Ij} is interfering power between the interfering node I and node j, $|h_{Ij}|^2$ is the channel coefficient between the respective interfering node and j^{th} node. Initially, the RF signal is converted into complex baseband signal and further signal conversion noise $n_{C,ij}$ is added to it. Next, analog-to-digital converter converts the incoming signal into digital signal. Later, it is forwarded to the ID unit. Hence, the digitized signal ($y^*(k)$) is given by (2):

$$y^*(k) = \sqrt{P_{ij}} h_{ij} \mathrm{x}[\mathrm{k}] + \sum_{I=i_1}^{i_m} \sqrt{P_{Ij}}\, h_{Ij} \mathrm{x}[\mathrm{k}] + n_{A,ij}[k] + n_{C,ij}[k] \quad (2)$$

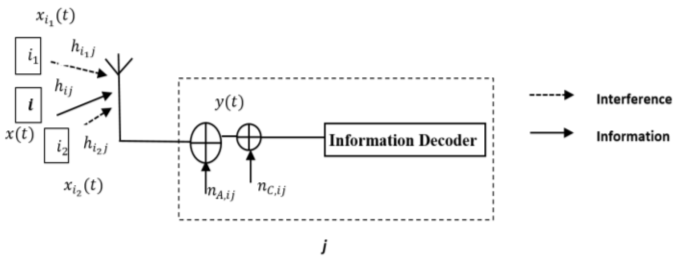

Figure 2. Basic IT receiver architecture

Therefore, the SINR of IT receiver ($SINR_{ij}^{IT}$) from the Figure 2 is given by (3):

$$SINR_{ij}^{IT} = \frac{|h_{ij}|^2 P_{ij}}{\left(\sigma_{A,ij}^2 + \sigma_C^2 + \sum_{i=i_1}^{i_m} P_{ij} |h_{ij}|^2\right)} \quad (3)$$

where, h_{ij} is the channel coefficient between i and j^{th} node, $\sigma_{A,ij}^2$ is the variance of antenna noise, σ_C^2 is the variance of signal conversion noise. Based on the $SINR_{ij}^{IT}$, the channel capacity at the receiver node j C_{ij}^{IT} is given by (4):

$$C_{ij}^{IT} = B * \log_2(1 + SINR_{ij}^{IT}) \quad (4)$$

where, B denotes the bandwidth of fading channel.

3.3.2. SWIPT-PS receiver

The basic SWIPT-PS receiver architecture is shown in Figure 3. Here, the receiver node j receives RF signal along with interference from transmitter node i. SWIPT-PS receiver architecture consists of EH unit and ID unit. Here, the noise emerging from antenna is common for both EH and ID units whereas signal conversion noise circuit exist only at ID unit. Hence, both antenna noise and signal conversion noise circuits are separated. The amount of RF signal fed towards both units is decided based on the PS ratio ($\alpha_{ij} = \alpha_{ij}^E + \alpha_{ij}^I$ and ($0 \leq \alpha_{ij} \leq 1$)) which is generated by the PS unit. Therefore, one part of PS ratio is fed to EH unit which is represented with α_{ij}^E and its output ($y^{EH}(t)$) is given by (5):

$$y^{EH}(t) = \alpha_{ij}^E y(t) \quad (5)$$

where, $y(t)$ is the received RF signal that is mentioned in (1). The total energy harvested by the EH unit is given by (6):

$$E_{ij}^{eh} = \varepsilon_j \alpha_{ij}^E (|h_{ij}|^2 P_{ij} + \sigma_{A,ij}^2 + \sum_{I=i_1}^{i_m} P_{Ij}\, |h_{Ij}|^2) \quad (6)$$

where, ε_j indicates EH coefficient of node j and it is $0 < \varepsilon_j < 1$.

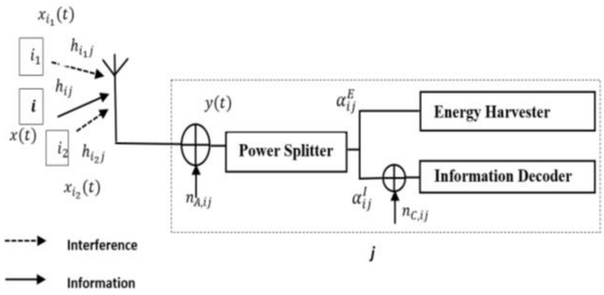

Figure 3. Basic SWIPT receiver architecture

The other part of PS ratio is fed to ID unit which is represented with α_{ij}^I and its output ($y^{ID}(t)$) is given by (7):

$$y^{ID}(t) = \alpha_{ij}^I (y(t) + n_{C,ij}(t)) \tag{7}$$

where, $n_{C,ij}(t)$ is signal conversion noise. Therefore, the SINR of the SWIPT-PS receiver circuit is obtained as (8):

$$SINR_{ij}^{SWIPT} = \alpha_{ij}^I \frac{|h_{ij}|^2 P_{ij}}{\left(\sigma_{A,ij}^2 + \sigma_C^2 + \sum_{I=i_1}^{i_m} P_{Ij} |h_{Ij}|^2\right)} \tag{8}$$

The channel capacity with SWIPT-PS is given by (9):

$$C_{ij}^{SWIPT} = B * \log_2(1 + SINR_{ij}^{SWIPT}) \tag{9}$$

when $\alpha_{ij} = \alpha_{ij}^I = 1$ then the SWIPT-PS receiver is similar to the IT receiver where only information is decoded, and no energy is harvested.

3.4. Proposed M-SWIPT receiver

Most of the past researchers on EH applied either TS or PS protocols in SWIPT. However, they have individual advantages and disadvantages. For instance, the PS protocol splits the signal for EH and ID in order to provide sufficient energy for data decoding and forwarding. However, PS suffers from serious problems when the signal strength is weak. The weaker signal can't provide sufficient amount of energy for EH and ID. In such case, the PS shows poor performance. On the other hand, the TS won't explore any details about the strength of signal. Even though more time is allocated for EH, the strength of the received signal must be more to ensure better network functioning. Hence, we combined both protocols to achieve better network performance in the IoT network in terms of both energy efficiency and EH. The proposed SWIPT architecture is called MSWIPT as it is a mixed form of TS and PS protocols and mainly intended for simultaneous EH and IT.

Under this model, sink node collects the data from all SNs that are located in the monitoring region in information collection intervals $(I_1, I_2, I_3 \dots . I_c)$, as shown in Figure 4. Moreover, the time duration for each interval is same i.e., $|I_1| = |I_2| = |I_3| = \cdots |I_c| = T$. Here, the total time duration T is divided into two unequal parts, they are θ and $T - \theta$. θ is dedicated for energy broadcasting and $T - \theta$ is dedicated for data transmission. Further, the data transmission slot (i.e., $T - \theta$) is divided into equal time periods like $(|t_1| = |t_2| = |t_3| = \cdots |t_p| = t)$. The value of time duration t_i is varied based on the number of SN and needs to satisfy the condition $\theta + pt \leq T$. It means that maximum p number of SN simultaneously transfers the data towards sink node. Here, a scheduling algorithm is used to avoid collisions between the data transmission and energy broadcasting slots [30].

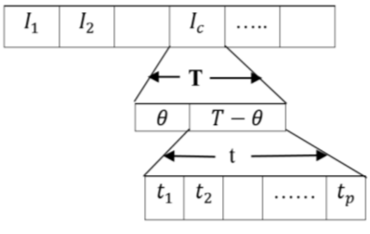

Figure 4. Structure of time slots partitioning

In the IoT network, each SN consists of TS, PS, signal processing, EH, and rechargeable units. Due to the constraints in hardware architecture, the circuit used for data processing is not attached to the EH unit. Therefore, the ID and EH units are separated from each other. Here, we consider constant power consumption for all SN in timeslot t_i for entire information collection and processing and neglect the power loss and noise produced during signal processing at PS and TS units. Here, we suppose one sink node and three SN. They are sender node, receiver node, and neighbor node to describe the working principle of proposed technique as shown in Figure 5. In time duration t_i, each SN can operate in any one of the three operating modes. They are wireless energy harvesting (WEH), wireless data transmission (WDT), and wireless data reception (WDR). The entire working principle is divided into two parts, one is sink node energy broadcasting and the other is simultaneous wireless information and energy transfer.

a. In time slot θ, the sink node broadcasts its energy to all SNs nodes in the network as indicated with dotted green arrow as shown in the Figure 5. Currently, all the SNs harvest the energy and store it into their rechargeable battery.
b. In time slot $(T - \theta)$ or t_i, all three nodes work independently in three operating modes.

– In the time slot t_i, for sender node *i*, TS switches to WDT mode and it transfers the desired information to the receiver node *j* and energy to its neighbor nodes simultaneously as shown in the Figure 5 and it is indicated with red solid line and only energy flow is indicated with black dotted line.
– In the same time slot t_i, for receiver node, TS switches to WDR mode and receives desired RF signal and forwards to PS unit. In PS unit, the received signal split into two parts based on the splitting ratio (α_{ij}). One part of signal is fed into ID unit with the splitting ratio α_{ij}^I and other part is fed into EH unit with the splitting ratio α_{ij}^E where, α_{ij}^I and α_{ij}^E are PS ratios for ID and EH respectively. Next, the energy harvested during this time duration is collected in rechargeable battery for further data transmission.
– Meanwhile, in the same time duration t_i for the neighbor node (neither send nor receive any data), TS switches to WEH mode and harvest the energy from surrounding unintended nodes other than sink. Later, the harvested energy is stored into a rechargeable battery.

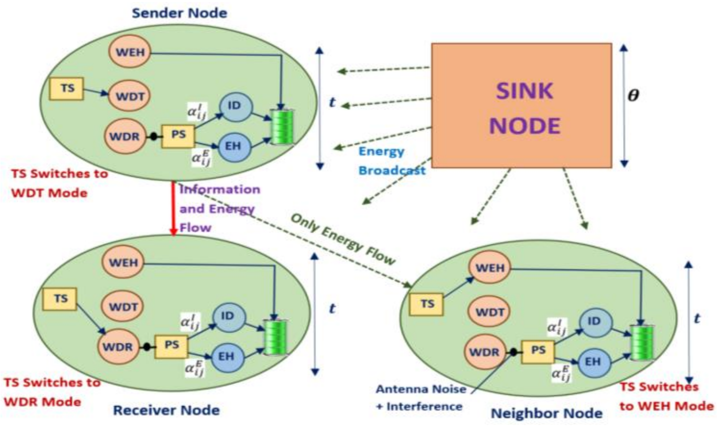

Figure 5. Working principle of proposed mechanism

Here, the proposed system harvests the energy using multiple sources in each time slot and stores it in rechargeable battery for further usage. Therefore, the total harvested energy is the accumulation of each source's harvested energy, and it is given by (10):

$$E_H = E_{past-hop\ node} + E_{sink} + E_{IN} + E_{nn} \tag{10}$$

where E_H denotes overall harvested energy at receiver node *j*, $E_{past-hop\ node}$ represents the energy harvested at node *j* by RF signal transmitted from node *i*, E_{sink} denotes the energy harvested by the receiver node due to sink broadcasting power, E_{IN} represents the total harvested energy from antenna noise and co-channel interference, and E_{nn} denotes the energy harvested from its unintended neighbor nodes.

a. $E_{past-hop\ node}$: initially in the time slot θ, the sink node broadcast energy into the network and all other nodes harvest energy and store it in their rechargeable battery. In the next time slot t, the remaining three nodes work simultaneously in different modes.

According to our proposed work, this work computes total harvested energy analytically from all the sensors in the network. The maximum harvested energy by receiver node *j* in time duration t_i from sender node *i* is given as (11):

$$E_{past-hop\,node} = \sum_{i=1}^{m} P_{ij}\varepsilon_j\eta_{ij}\alpha_{ij}^{E}h_{ij}\,t_i, m \in N \tag{11}$$

where, $E_{past-hop\,node}$ indicates the energy harvested from node *i* at node *j*, m denotes set of transmitting nodes, P_{ij} indicates the transmitted RF signal from node *i* to node *j*, ε_j indicates EH coefficient of node *j* and it is $0 < \varepsilon_j < 1$, α_{ij}^{E} indicates PS ratios for EH, h_{ij} indicates channel gain coefficient, and η_{ij} indicates RF-DC conversion coefficient and it is $0 < \eta_{ij} < 1$. The energy conversion coefficient and transmit power are interlinked with each other. As the transmission power increases η_{ij} also increases until it reaches stable point i.e., η_{ij}=0.8.

b. E_{sink}: the harvested energy due to sink broadcasting power P_{sink} at the receiver node *j* in time slot θ is given by (12):

$$E_{sink} = P_{sink}\varepsilon_j\eta_{ij}h_{ij}\theta \tag{12}$$

where, E_{sink} denotes energy harvested by the receiver node *j* from the broadcasting power P_{sink}, and P_{sink} is the sink broadcasting power.

c. E_{IN}: the harvested energy from to co-channel interference (CCI) and antenna noise by the receiver node *j* in time slot t_i is given by (13):

$$E_{IN} = \sum_{i=i_1}^{i_m}(\sigma_{A,ij}^2 + \sigma_{CCI,ij}^2)\eta_{ij}\alpha_{ij}^{E}\,t_i \tag{13}$$

where, E_{IN} denotes energy harvested due to CCI and antenna noise by the receiver node *j*, $\sigma_{A,ij}^2$ indicates AWGN produced at receiver *j*, $\sigma_{CCI,ij}^2$ indicates total CCI at receiver node *j*.

d. E_{nn}: the harvested energy from k number of undesired neighbor nodes (neither receive not transmit any kind of data) in the time interval t_i is given by (14):

$$E_{nn} = \sum_{i=1}^{k} P_{ij}\varepsilon_j\eta_{ij}h_{ij}\,(1 - x_{ij})t_i, k \in N \tag{14}$$

where, E_{nn} represents total harvested energy from undesired neighbor nodes, k denotes neither transmitting nor receiving neighbor SN, x_{ij} indicates binary indicator. If x_{ij} equal to 1 then the corresponding neighbor node is busy with either transmission or reception and if it is zero, then it harvests the energy from undesired neighbor nodes.

Here, the amount of harvested energy varies based on the sink broadcast time slot (θ) and PS ratio for EH (α_{ij}^{E}). Similarly, the amount of ID is also depending on the PS ratio for ID (α_{ij}^{I}). The proposed system not only concentrates on EH but also on IT rate. If α_{ij}^{I} decreases, θ increases then the data transfer rate decreases. In addition, if transmitted power decreases or if the received RF signal is more interfered with other signals then the amount of harvested energy and IT rate alters. Similar to (3) and (8), the proposed method's SINR is expressed as (15):

$$SINR_{ij}^{M-SWIPT} = \frac{\alpha_{ij}^{I}|h_{ij}|^2 P_{ij}}{\left(\alpha_{ij}^{I}\sigma_{A,ij}^2 + \sigma_C^2 + \alpha_{ij}^{I}\sum_{I=i_1}^{i_m} P_{Ij}|h_{Ij}|^2\right)} \tag{15}$$

In (15) represents the SINR of M-SWIPT, where the TS and PS protocols are involved. During the $(T - \theta)$ time slot, the information is decoded according to the PS ratio α_{ij}^{I}. The channel capacity with M-SWIPT ($C_{ij}^{M-SWIPT}$) is given by (16):

$$C_{ij}^{M-SWIPT} = B * \log_2(1 + SINR_{ij}^{M-SWIPT}) \tag{16}$$

According to the proposed method, the information rate and harvested energy completely depends on the splitting ratio and transmitting power. Moreover, it concentrated on the influence of interference on the SWIPT receiver. Due to interference, SINR decreases, and the quality of IT reduces. But the proposed method considered interference is one of the valid EH source. Therefore, to improve the overall system performance in concern with the above issues, we formulated link capacity-based energy and information allocation problem. Hence, based on (9), (15), and (16), maximization of link capacity with interference is formulated as (17):

$$\begin{aligned} &\max_{\alpha_{ij},P_{ij}} C_{ij}^{M-SWIPT} \\ &s.t.\, C_{ij}^{M-SWIPT} = B * \log_2(1 + SINR_{ij}^{M-SWIPT}) \\ &SINR_{ij}^{M-SWIPT} = \frac{\alpha_{ij}^I |h_{ij}|^2 P_{ij}}{\left(\alpha_{ij}^I \sigma_{A,ij}^2 + \sigma_C^2 + \alpha_{ij}^I \sum_{I=i_1}^{i_m} P_{Ij} |h_{Ij}|^2\right)} \\ &E_H = E_{past-hop\, node} + E_{sink} + E_{IN} + E_{nn} \\ &P_{ij} \in [0, P_{max}] \\ &\alpha_{ij} \in [0, 1] \end{aligned} \tag{17}$$

In (17) represents the maximization of link capacity subject to obtained link capacity, SINR, and EH for M-SWIPT. Generally, link capacity deals with IT but the proposed work also considered EH through multiple sources. IT and amount of energy harvested majorly depends on the PS ratio, TS ratio, and transmitted power. The detailed algorithm for the proposed work is appended in Algorithm 1.

Algorithm 1. Proposed M-SWIPT receiver algorithm

Input: P_{max}, T
Output: Link Capacity at node j i.e., $C_{ij}^{M-SWIPT}$
for harvested energy **do**
Measure the harvested energy E_{sink} in time duration θ using Eq. (12)
for EH in time duration $(T-\theta)$ **do**
Measure the harvested energy $E_{past-hop\, node}, E_{IN}, and\, E_{nn}$ in time duration $T-\theta$ simultaneously using Eq. (11), Eq. (13), and Eq. (14) respectively.
end
Calculate total harvested energy using Eq. (10)
end
for $SINR_{ij}^{M-SWIPT}$ **do**
Measure $SINR_{ij}^{M-SWIPT}$ using Eq. (15)
end
for Maximum Link Capacity **do**
Compute $C_{ij}^{M-SWIPT}$ using Eq. (17) by considering optimum values of α_{ij}, P_{ij}
end

4. EXPERIMENTAL ANALYSIS

This section explores the details of simulation experiments conducted on the proposed approach through different network parameters. At first, the details simulation set up are explored, i.e., the set up established to conduct the experiments. Next, the efficiency of the proposed approach is explored in terms of different network parameters like maximum transmit power, node count and varying interference power. Finally, the performance of the proposed approach is compared with the performance of existing methods.

4.1. Simulation set up

Table 2 shows the simulation set up established to conduct experiments on the proposed approach. For simulating the proposed model, we used MATLAB 2018 tool, and the example functions used to realize the network concept is *Rand*. With the help of this command, we created a random network with *N* number of nodes each have two positions, they are *x*-position and *y*-position. Due to *Rand*, the positions of nodes are not constant, and they change for every simulation which in turn changes the topology of the network. Based on the node count (ranging from 20 to 40) the network area also changes and its lies within the range of 200×200, 250×250, 300×300, 350×350, and 400×400. For every node, the initial energy is providing as 2 mJ which is stored in their rechargeable batteries. Here we considered a small-scale Rayleigh fading channel with flat in nature. The maximum allowed power to transmit by sink varies from 0.01 to 0.05 watt and the power of interference is varied from 0 dB to 15 dB with an interval of 5 dB. The minimum energy needed to harvest is fixed to 10% of the maximum power transmitted from any transmitter node. PS ratio α_{ij} is varied between 0.2 to 0.8 and total time is considered as 30 seconds. Antenna noise is considered as -10 dBm, minimum transmitted power as 5 milli watts.

Table 2. Simulation set up

Parameter	Value
α_{ij}	[0.2 0.4 0.6 0.8]
P_{Sink}	[0.01 0.04 0.06 0.08] watt
T	30 s
t_i	1 s
$\sigma^2_{CCI,ij}$	[0 5 10 15] dBm
$\sigma^2_{AN,ij}$	-10 dBm
P_{min}	0.005 watt
P_c	0.001 watt
ε_j	1
N	20, 30, and 40
Area	200×200, 250×250, 300×300, 350×350, and 400×400

4.2. Results

This section illustrates the complete details of proposed methods performance in terms of performance metrics like average energy efficiency (AEE), and AHE. These two-performance metrics are computed with respect to different varying parameters like maximum transmit power, node count, network area, interference power, sink broadcasting time, and sink broadcasting power.

4.2.1. Average energy efficiency

AEE is defined as the number of bits received by the sink node per joule energy consumption:

$$AEE = \frac{t\sum_{i,j=1}^{N}(B*\log_2(1+SINR_{ij}^{M-SWIPT}))}{E_{Tc}}$$

where, E_{Tc} represents the total energy consumed during the transmission and it is computed as:

$$E_{Tc} = P_d T + \sum_{i,j=1}^{N} \mu P_{ij} t - \sum_{j=1}^{N} E_H^j$$

where, first term indicates the fixed power consumed by all SN during T, second term indicates total energy consumed in the transmitter's power amplifier, where $\mu \geq 1$, represents inefficacy of the power amplifier, and third term indicates total harvested energy using multiple sources at receiver node j.

Figure 6 explores the impact of varying maximum transmit powers on the AEE. From the result, we can see that the AEE follows a monotonic increasing relation with the maximum transmit power. Since the rise in the maximum transmit power allows the nodes to harvest more energy and also enhances the SINR, the nodes can forward the data to the corresponding destination nodes with high transmit power. We observed the maximum AEE at the 0.03 watt maximum transmit power because the proposed approach gained a tradeoff between energy efficiency, power utilization and AHE of the system. After reaching the system to an optimal value, its AEE decreases because nodes have limit regarding the utilization of available power. Even though we employed interference as a source of energy, it helped in a limited manner to increase the AEE because the harvested power is utilized to compensate co-channel interference between nodes and hence the extra gain achieved is very limited.

Figure 7 explores the impact of varying maximum transmit powers on the AHE. From the results, it can be observed that the AHE is low for lower maximum transmit power rates because the lower transmit power allows the nodes to harvest only a little amount of energy as it needs to support for ID also. Such kind of process limits the energy efficiency of the system. On the other hand, the larger transmit power allows the nodes o to harvest more energy until the nodes become stable and capable of forwarding the data to further nodes. Upon getting saturated, i.e., harvesting the minimum amount of energy required and attaining minimum data rate at receiver, the nodes increase the transmission power to attain energy efficiency. In the current simulation study, we observed the saturation point as 0.03 watt. Furthermore, the AHE is more at larger CCIs as we consider it as one of the sources of energy. Compared to the single source, the multiple sources ensure more AHE.

Figure 8 shows the comparative analysis between proposed and existing methods through AHE with varying Maximum transmit power. From the comparison, it can be noticed that the proposed SWIPT mechanism had harvested more energy than all the existing methods such as SWIPT-PS [10], SWIPT-TS [26], hybrid SWIPT with single source (HSWIPT-SS) [27]. The main reason is that the proposed approach uses multiple sources for EH which is completely different from existing methods those were used only one source for EH. In the proposed architecture, the nodes have flexibility to harvest energy from multiple sources, hence they can harvest more energy. On an average, the proposed approach harvested energy of

0.7020 joules while the existing methods such as SWIPT-TS, SWIPT-PS, and HSWIPT-SS harvested only 0.3280 joules, 0.4580 joules, and 0.5180 joules respectively. Further, we observed that the stable point is reached at the maximum transmit power of 0.03 watt.

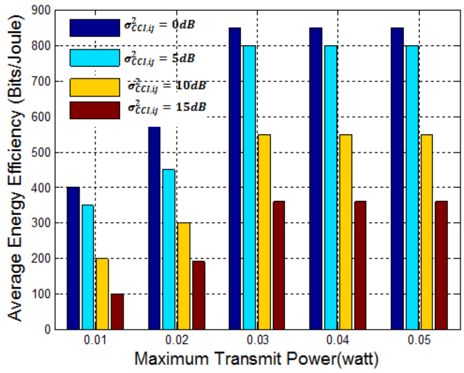

Figure 6. AEE for varying maximum transmit power and interference power

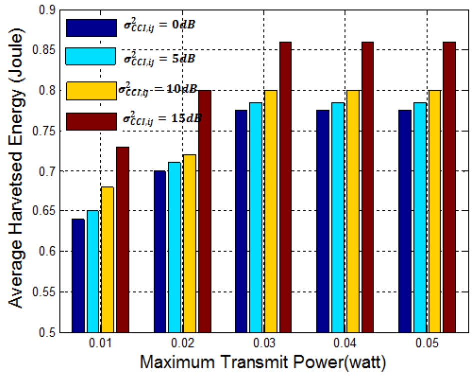

Figure 7. AHE for varying maximum transmit power and interference power

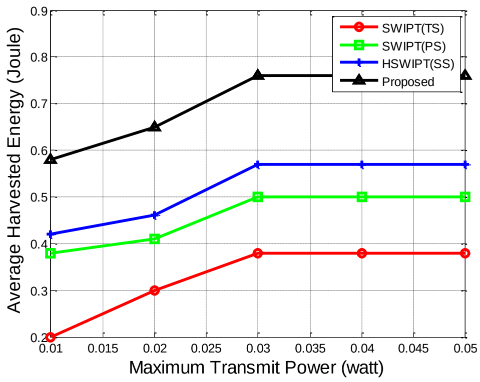

Figure 8. AHE efficiency comparison at different maximum transmit powers

Figure 9 shows the comparative analysis between proposed and existing methods through AEE with varying maximum transmit power. The comparison shows that the proposed approach outperformed the existing methods by attaining maximum AEE at all cases of maximum transmit power. Here, we can see that the SWIPT-PS AEE is better than the SWIPT-TS. In the case of weak signal, the maximum transmit power received at receiver node is subjected to splitting; it results in inadequate ID and EH. Because the power split in signal is used to trigger the ID or EH circuit and the amount of energy left for EH and ID is very less. Hence, at lower transmit powers, the existing methods shows very poor performance. Compared to the single protocols, the hybrid SWIPT gained more AEE but not more than proposed methods. As it used only single source for EH, the gained energy is almost used for multiple purposes like EH and ID. Further, it is noticed that the AEE of all the methods increases with the rise in the maximum transmit power until an optimal AEE and it becomes stable after 0.03 Watt. However, the proposed approach gained approximately 901 bits/joule at stable transmits power while the existing methods such as SWIPT-TS, SWIPT-PS, and HSWIPT-SS gained only 830, 810, and 700 bits/joule respectively. Since the proposed approach is a combined form of TS and PS protocols and uses multiple sources for EH, it can decode the information effectively.

Figure 10 shows the AEE with varying sink broadcasting time and sink broadcasting power. From the result, we can see that the rise in sink broadcasting time and power raises the AEE because for the larger values of θ and P_{sink}, the nodes can harvest more energy from the sink. This additional harvested energy supports transmitting the data with high transmit power to the next hop neighbor nodes. Such transmission improves the SINR at the receiver node and makes the nodes decode the information accurately and helps in increasing the AEE. Further, we noticed that the AEE has reached to its maximum value at $\theta = 5s$ because the system attained a tradeoff between information gathering time by sink and EH time.

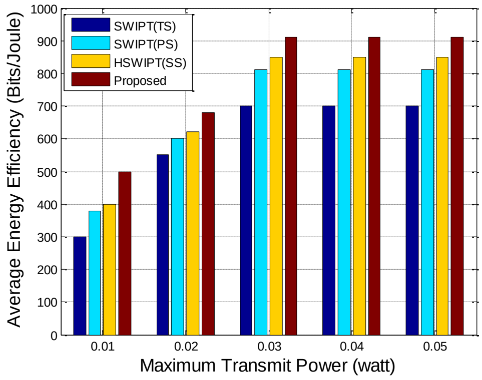

Figure 9. AEE comparison at different maximum transmit powers

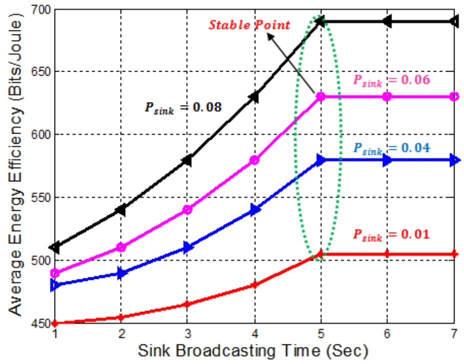

Figure 10. AEE for varying sink broadcasting time at different sink broadcasting time slots

Figure 11 explores the impact of network area and node count over the AEE of the IoT network. From the result, we can see that increase in the network area decreases AEE. The reason is twofold: i) as the network area increases, the distance between nodes increases and to transmit the data to distant nodes, the sender nodes require more energy and also experiences the attenuation effect in the signal and ii) the larger distance between nodes limits the harvesting energy by the receiver node. The increased attenuation decreases the SINR at receiver node which in turn shows impact on the data rate followed by AEE. Further, it can also be observed that the larger count of nodes has achieved larger AEE than the lower node count. For a fixed area of network with a larger node count, the distance between nodes is very less which reduces the energy consumption and increases the AEE. Tables 3 and 4 show the percentage of improvement of AHE and AEE under varying maximum transmit power.

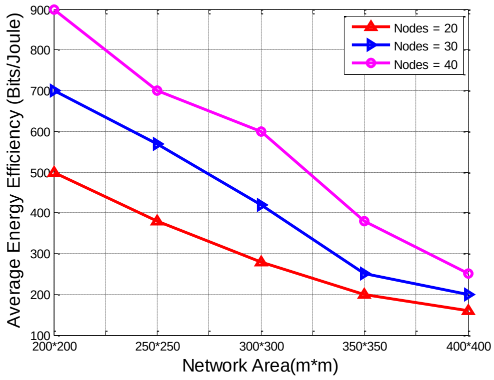

Figure 11. AEE for varying network area and node count

Table 3. Improvement of AHE under varying maximum transmit power

Method	AHE (joule)	% of improvement in AHE
SWIPT-TS	0.328	53.27
SWIPT-PS	0.458	34.76
HSWIPT-SS	0.518	26.21
Proposed (HSWIPT-MS)	0.702	-

Table 4. Improvement of AEE under varying maximum transmit power

Method	AEE (bits/joule)	Improvement of AEE (%)
SWIPT-TS	590	24.74
SWIPT-PS	684	12.75
HSWIPT-SS	712	9.18
Proposed (HSWIPT-MS)	784	-

5. CONCLUSION

Most of the existing works considered single source such as past-hop node's RF signal to harvest the energy in energy constrained IoT networks. This paper proposed multi-source-based EH mechanism namely M-SWIPT for multi-hop IoT networks which integrates TS and PS protocols. Here, multiple sources such as past-hop node's RF signal, non-participated neighbor Node's RF signal, sink node's broadcasting energy, and co-channel interference are considered to measure the total harvesting energy. Further, this work not only concentrated on harvesting energy but also on IT. Next, the information and energy allocation problems are addressed through link capacity by maintaining optimal transmission power and PS ratio. Further, the proposed work's performance is measured through two metrics namely AHE and AEE by varying maximum transmit power, interference levels, sink broadcasting time, and number of nodes. Finally, the results shown superiority of the proposed method over state-of-the art methods. The proposed M-SWIPT method shown the improvement in AEE as 24.74%, 12.75%, and 9.18% compared to SWIPT-TS, SWIPT-PS, and HSWIPT-SS.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors have no material competing interests, either financial or otherwise. Moreover, the authors have no declared conflicting interests that are pertinent to the subject matter of this study.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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