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Green Computing in IoT: Time Slotted Simultaneous Wireless Information and Power Transfer

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Abstract

Simultaneous Wireless Information and Power Transfer (SWIPT) is an emerging field to transmit information and power in IoT network through the same RF signal. Time switching (TS) protocol is more favorable in free space communication than Power Splitting (PS) protocol when the transmitted RF signal is already weak. This is because, transmitted signal loses its power due to attenuation in free space, and using PS design receiver circuit (complex), the received weak signal is further split into two fraction for energy harvesting (EH) and information decoding (ID) simultaneously, that causes inadequacy in SWIPT system. Whereas, using TS design receiver circuit (simple) insert extra delay in the network as EH and ID operations are done in two different time domain one by one. Literature on SWIPT lacks towards cooperation between more energy harvesting in case of free space communication (TS) and critical information transmission in case of delay constraint communication (PS). In this context, this paper presents a time-slotted SWIPT (T-SWIPT) focusing on maximization of energy efficiency in the relay based sensors-enabled IoT network. It enables simultaneous energy harvesting at receiver and neighboring sensors without adding extra delay in the network. The PS ratio, transmission power allotment and energy broadcast time are jointly formulated as non-convex energy efficiency maximization problem. A solution to the problem is presented using Lagrangian dual decomposition and fractional programming. The performance evaluation shows that T-SWIPT attains optimum energy efficiency by trading off transmission power allotment, power-splitting ratio and sink broadcast time slot.

Keywords

Green computing; Energy optimization; Lagrangian dual decomposition; Internet of things.

1. Introduction

Internet of Things (IoT) provides massive connectivity among sensors, smart phones, wearable smart healthcare devices, smart home devices, smart military equipment and many more [1-2]. In order to deal with massive terminal device connectivity, wireless networks are extended to next generation 5G-IoT network to provide higher data rate by reducing the energy consumption of network [3]. According to Statista research, the number of connected devices in IoT network is projected around 75.44 billion worldwide by 2025 [4]. Most of these smart devices in the present era are simply 'linked sensor nodes' having limited battery capacity. In Green computing, EH emerges as a viable mechanism to increase the lifetime of the sensors-enabled IoT network uninterrupted, by refilling the batteries of sensors in an environmentally sound manner [5]. EH mechanism mainly divided into two categories including harvest energy from the natural resources such as wind, solar, vibration, ambient heat which is termed as conventional EH technique, and harvest energy from rich-energy sources that emit electromagnetic waves such as strong magnetic inductive coupling (SMIC) and radio frequency (RF) signals which is termed as wireless power transfer (WPT) [6, 9].

The conventional EH techniques provide better amount of energy to energy-hungry sensors, but their availability varies with temperature, time, location and other conditions [7]. In addition, these energy sources may not always be available for enclosed/indoor environment. Therefore, inherent randomness feature and lack of reliability makes the resource allocation problem in the wireless sensors-enabled IoT network challenging. Thanks to WPT technique, where RF signals are also capable of carrying energy in the range of 300 GHz to 3 KHz frequency band that ensure reliable energy source and provide sufficient amount of energy in controlled, predictable and stable manner to low-powered sensors [8]. SMIC with mobile wireless charging node has attracted more attention from researches [9-10]. However, there are certain limitations such as SMIC is not available in hostile environment (steep mountains and wild forest) because mobile wireless nodes cannot migrate or travel. On the other hand, WPT implemented with external charger (high energy-rich sources) to distribute only energy to low-powered devices put extra cost to the system. In addition, there is another major concern about fast attenuation problem i.e., loss of power in the energy transfer efficiency over far field communication. Consequently, these problems put limitations on use of WPT with RF signals for only energy transfer. Therefore, a new technique has been emerged known as SWIPT, which transfer information and energy simultaneously in the same RF signals to improve the energy transfer efficiency and remove the cost of extra charger used by rechargeable batteries in sensors-enabled IoT network [6]. In SWIPT, receiver uses same received RF signal for ID and EH, whereas in conventional WPT, RF signal received by a node is only used for EH.

For practical implementation of SWIPT technique, the receiving node has two different circuits to execute the function of EH and ID [11]. There are two different types of protocols namely, time switching (TS) or power-splitting (PS) used at the receiver to implement SWIPT. In TS design receiver, total operational time is divided into two time slots, the whole received signal is first sent to EH circuit for harvesting energy according to TS ratio, and then sent for ID. Whereas in PS design, received signal splits into two signals according to PS ratio, one part of the received signal is sent for EH and another part for ID simultaneously for whole operational period [12]. There is a tradeoff between EH and ID ratio in both of these protocols [13]. If larger splitting ratio (more time spend in TS protocol or greater portion of received signal in PS protocol) is provided for EH, then receiver is able to harvest greater amount of energy at the cost of lower data rate, as less amount of information decoded for smaller splitting ratio. Overall, unbalanced splitting ratio caused in TS or PS protocol decreases the system energy efficiency. Therefore, there is a need to develop novel algorithm for proper allotment of resources in SWIPT technique towards improving the system energy efficiency.

SWIPT technique for EH has been the key focus area for the researchers to improve the system performance [14-20]. Most of them have used either TS protocol or PS protocol such that minimize power consumption in sending large number of bits and harvest more energy from received RF signals subject to improve system energy efficiency. In [14], authors have claimed that for higher SINR value, PS protocol outperforms TS protocol in terms of energy harvesting in multi-hop relay based wireless sensor network. Moreover, for lower SINR value TS protocol provide higher throughput than PS protocol. From [25-29], authors have used both TS and PS protocol to develop hybrid model in sensor network and show that hybrid protocol outperforms the TS or PS enabled SWIPT protocol in terms of data rate (throughput), energy harvesting and energy efficiency. However, in the above literatures sensor node has used only the source node's RF signal for energy harvesting and it left out neighbors' (unintended transmitters) RF signals, which is a valid source of energy and has a notable impact on energy efficiency of the system. We argue these points due to the necessity of both PS and TS protocol to harvest additionally more energy in sink broadcast time and EH from unintended (neighbor node) transmitted RF signals in the network.

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In this context, this paper proposes a novel T-SWIPT technique that integrates both TS and PS design protocol in the sensor node (see Fig. 3 in Section 3.2) in order to enhance the energy efficiency of sensors-enabled IoT network. In this architecture design, sensor node not only harvests energy from sink node in TS mode but also harvests energy from its intended received signal working in receiving mode, and from any unintended transmitters (neighbors) when it is neither transmitting nor receiving any information at any particular time slot in PS mode. However, integration of TS and PS mode protocol put extra financial cost on the architecture design of the receiver circuit. In paper [13, 41-42] researchers have found that energy harvesting and information decoding capability of the sensor node have been highly enhanced over cost. Further, the studies show that consumption of energy in integrated receiver circuit architecture is relatively smaller as compared to co-located (TS/PS) receiver circuit because rectifier integrates the RF-to-baseband conversion for ID with EH circuit into single chip by minimizing the RF flow form factor, which in turn enhances the energy harvesting capability in integrated receiver architecture. Further, extra PS circuit dynamically split the received signal into two signals to gain additional energy (separate from sink or any other unintended transmitter) and information simultaneously. Thus, hybrid design protocol provides us flexibility to adjust power spend on information decoding and energy harvesting by adjusting appropriately the PS and TS ratio. Further, throughput of the network can be improved on increasing the maximum allowed transmitted power region, as higher transmitted power enhances the SINR value at receiver side, in turn higher number of bits are successfully decoded.

Motivated by the above mentioned challenges, obtaining optimal transmitted power, power splitting ratio and time switching ratio is more concerned metrics rather than financial cost of hybrid design sensor node, subject to energy harvesting and throughput of the network. Thus, this paper presents a novel T-SWIPT technique to maximize the overall energy efficiency of the network by jointly selecting the optimal PS ratio, TS ratio and computing the optimal transmit power which as a result provide optimal throughput between transmitter and receiver.

1.1. Our contributions

Our major contributions of the paper are given as follow-

1) Firstly, T-SWIPT technical architecture is presented for EH by receiving node and other neighbor nodes from the ambient RF signals and from the broadcasted energy signal by sink.
2) Secondly, we derive the problem of energy efficiency focusing on optimal transmit power, PS ratio and time slot for the sink energy broadcast as a non-convex maximization problem. After that, the formulated problem is converted into a corresponding subtractive convex maximization problem to find the solution.
3) Thirdly, the maximization problem is solved by utilizing the iterative Lagrangian based optimization for allotment of optimal transmit power, PS ratio and sink energy broadcast time.
4) Fourthly, the convergence and complexity of the presented algorithm is analyzed. It is proved that our presented algorithm converges within less number of iterations in polynomial time.
5) Finally, simulations are presented to analyze the performance of the proposed T-SWIPT technique in optimizing the energy efficiency of the network.

1.2. Organization

We organize the rest of the paper into the following sections. Section 2 describes the related works on energy harvesting in IoT. Section 3 presents the T-SWIPT technique for energy harvesting in IoT. In section 4, energy efficiency optimization problem is formulated and solved. Section 5 discusses the simulation results and its analysis. Finally, the conclusion of the paper is given in section 6. The notations used in the paper are given in Table 1.

Table 1. Nomenclature

Notation	Description
P_{ij}	Transmission power used by transmitter i to transmit data to receiver j
g_{ij}	Channel power gain between transmitter i and receiver j
$\tau_{ij} = \tau_{ij}^{I}$	Power splitting ratio for ID
$1 - \tau_{ij} = \tau_{ij}^{E}$	Power splitting ratio for EH

τ_{min}^{I}	Lower bound for power splitting ratio for ID
τ_{max}^{I}	Upper bound for power splitting ratio for ID
τ_{min}^{E}	Lower bound for power splitting ratio for EH
τ_{max}^{E}	Upper bound for power splitting ratio for EH
T	Information collection period
β	Sink energy broadcast slot
t	Data transmission slot
V	Channel bandwidth
$\sigma_{I,i,j}^{2}$	Co-channel interference received by receiving node j while receiving data from transmitting node i
$\sigma_{A,i,j}^{2}$	Additive white Gaussian noise (AWGN) powers emerging from receiver j antenna
$\sigma_{S,i,j}^{2}$	Noise power generated by processing of signal at receiver j
X_{ij}	Channel's capacity between transmitting sensor i and receiving sensor j
a_{ij}	It is a binary indicator, indicates whether sensor j harvest energy from unintended transmitter i or not.
D_{ij}	Data rate between transmitting node i receiving node j
E_{TH}^{j}	Total amount of EH by the receiver sensor j
η_{ij}	Energy conversion efficiency between transmitter i and receiver j
ε_j	Energy harvesting coefficient of receiver j
d	Number of sensor nodes that use sensor $j$as relay node
δ_{ij}	Priorities of different receiver nodes
P_c	Fixed power consumed by the transmitters and the receivers
μ	Inefficacy of the transmitter's power amplifier
D_{min}	Minimal sensed information rate requirement
E_{min}	Minimal energy harvesting requirement
P_{max}	Upper bound on the power emitted by the transmitter
P_{min}	Lower bound on the power emitted by the transmitter
P_s	Sink broadcast power
N	Number of sensor nodes
ψ	Average system energy efficiency
m	The number of unintended transmitters from which the sensor node harvest energy when it is not receiving or transmitting information.
c	Total number of slots for information transmission in an information collection period T.

2. Related work

In this section, related literature on SWIPT technique for energy harvesting is reviewed [12-26]. SWIPT emerges as a powerful EH technique that has been used in different wireless communication networks to improve energy efficiency of the network. A routing method with SWIPT has been considered to increase the lifetime of energy-limited sensor nodes and to minimize the network cost in a multi-hop energy constrained wireless network [11]. Specifically, the energy consumption minimization problem has been mathematically formulated in terms of data and energy allocation of network's forwarding link and solved by an iterative algorithm. Moreover, PS mode of SWIPT has been used with optimal PS ratio for minimizing energy consumption. Similarly, a relay based wireless communication network has been considered with decode and forward relaying technique for both TS and PS protocol [12]. From the simulation results it has been observed that the TS protocol is better than the PS protocol for different performance parameters, such as outage probability, bit error rate and throughput in high data transmission rate. However, in low data transmission rate PS protocol is better than TS, although overall performance decreases compare to high data transmission rate.

A multi-hop routing algorithm for data forwarding with SWIPT-PS and without SWIPT scheme has been proposed in order to minimize the energy consumption [15]. Authors have mainly focused on

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choosing either of the data-forwarding schemes based upon link energy cost, towards minimizing the transmission power regardless of the increasing data rate. Thus, overall energy efficiency and delay in the network decreases. A downlink TS-SWIPT technique is used to increase the energy efficiency [16-17]. Authors have mainly focused on minimizing the harvested energy per user in order to increase transmit power in multiple-input multiple-output (MIMO) network [16]. Whereas in [17], authors have focused on jointly maximize the total energy harvesting power in the network corresponds to satisfy the minimum data rate between the base station and the selected single receiver. Somehow, simulation results lack to show the behavior of network data rate on increasing transmit power, and also the comparison against TS-SWIPT is missing in both the literatures [16-17].

Energy efficient communication in an orthogonal frequency division multiple access (OFDMA) system with PS-SWIPT technique has been proposed in terms of optimal resource allotment [18]. However, it has used only PS protocol for simultaneous ID and EH, which has disadvantage when the received RF signal power is too low in high interference level (multiple receiver) [19, 20]. Because, high interference further lower down the power of transmitted signal, and weak received signal is further split into two parts for simultaneous ID and EH. And, less amount of harvested energy is not enough for further transmission. Thus, overall data rate of the OFDMA system decreases. In addition, they did not consider the energy harvesting from the transmitted signal of neighbors' node when it is neither transmitting nor receiving any data and sensors simply remain idle. A zero-forcing beamforming and time switching mode for multiple input single output (MISO) SWIPT system has been used to improve the energy harvesting capability of sensor nodes referred as system sum rate optimization problem [21]. Authors have considered special scenario when the transmit power of the base station has been restricted to certain amount and showed that TS based algorithm is better than PS protocol, but for general scenario where base station is considered as energy–rich source, comparison between TS and PS protocol is absent in terms of EH and throughput of the network.

Resource allotment optimization problem based on SWIPT technology for continuous or discrete power splitting ratio has been suggested for mobile energy harvesting WSN [22]. In the suggested algorithm, only cluster head has used PS mode of SWIPT technique to harvest energy from its member nodes. However, cluster member nodes do not harvest energy from any other sources. So, overall system lifetime decreases, and also mobile collector induces extra delay in the network for collecting data from cluster head. In [23], authors have used PS-SWIPT technique to cooperative clustered WSNs. Here, authors have optimized the energy efficiency of the system by using optimal value of transmit power, PS ratio and selecting optimal relay. For selection of relay, cluster head broadcasts data and energy to all cluster members, then node which provides higher data rate is selected as relay node. In the selection process, cluster head loses energy and is not compensated by any energy-harvesting source. However, member nodes can only harvest energy from its intended received signal. Here problem arises when the received signal power from cluster head is too low and relay doesn't harvest enough energy to forward the data. In [24], network efficiency maximization and secure communication for cognitive radio secondary networks have been considered as an optimization problem, which has been addressed by using SWIPT technique to optimize the three objectives: minimizing transmission power, increasing energy harvesting efficiency and minimizing interference-power-leakage-to-transmit-power ratio. However, the energy harvesting capability of the idle primary receivers has not been considered in the proposed minimization problem of transmission power and it has only given attention on the need of secure communication.

In [25], hybrid of TS and PS SWIPT protocol with beamforming technique has been considered in a full-duplex MIMO system to achieve optimal system throughput by optimizing the transmit power and TS ratio. Sensors harvest energy only from the signal transmitted by base station and signals transmitted by neighbor nodes has been neglected for energy harvesting. Whereas in [26], authors have considered three-node relaying network to forward data to destination using hybrid power-time switching protocol (HPTSR). Simulation results show that HPTSR is better than both amplify-forward (AF) relay and decode-forward relay against TS and PS protocol. In [27-28], AF relay is used for data forwarding by using energy harvested through sources in the proposed hybrid TSR and PSR algorithm. The optimal value of PS and TS ratio has been obtained to optimize the outage probability and system throughput. Moreover, the relay node works in half-duplex mode and authors have not compared it with decode and forward (full duplex mode) relay. In [29], authors have proposed adaptive time-power switching relay protocol, where AF relay harvests energy from the received signal and after that uses the harvested energy to forward the information in remote wireless network. Simulations show that network throughput in term of low ratios of signal-to-noise and higher packet delivery rate are better in time switching relaying protocol than power splitting relaying protocol. Further, it has been observed from [25-29] that hybrid protocol performs better than PS or TS protocol, and enhances network performance. However, the existing papers on hybrid technique lacks in proper utilization of unintended transmitters' signals (neighbor nodes) for energy harvesting, when sensors remain idle (neither transmitting nor receiving any information). Moreover, the relay node has used only the source node's RF signal for energy harvesting and it left out neighbor's RF signals, which is a valid source of energy and that have a notable impact on energy efficiency of the system.

3. T-SWIPT Technique for Energy Harvesting

In this section, we present T-SWIPT technique for energy harvesting by using both TS and PS protocol to increase the energy efficiency of the relay-based IoT network. For simplicity (see Fig. 1), a transmitting node sends data to sink node via multipath (using other nodes as relay), and other neighboring sensor nodes (neither transmitting nor receiving data) are able to harvest energy from the unintended transmitting node in time slotted manner. The harvested energy in current time slot is stored into rechargeable battery for further use in next time slot (harvest-store-then-cooperate) [30-31]. It is also assumed that, initially all the sensors are provided with some amount of energy but not fully charged. It improves the green aspect of sensor-enabled IoT network.

Each sensor node has three types of operation mode (DT/DR/EH) in its own time slot, but at a time, only one operation mode is activated in its time slot. When the sensor node works in data transmission (DT) mode (i.e. source node), it is able to transmit both information and energy (RF signal) in its transmitting slot. When the sensor node works in data receiving (DR) mode (i.e. relay node), it inherently uses PS protocol to split the received RF signal into two signals for information decoding and harvesting energy simultaneously in its own time slot. When the sensor node works in energy harvesting (EH) mode (neither transmitting nor receiving data), it is able to harvest energy from other neighbor transmitting node (unintended transmitter) in its time slot. Therefore, the proposed T-SWIPT technique enables the sensors to harvest additional energy from the other transmitting node in the EH mode rather than harvest energy only in DR mode of conventional PS design sensor node.

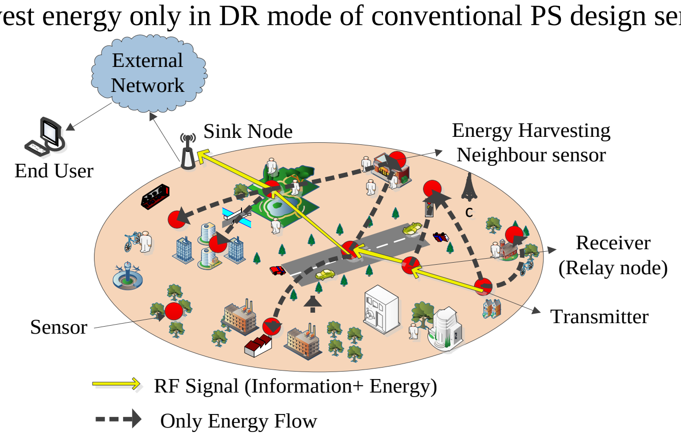

Fig. 1. Illustration of SWIPT technique in relay-based energy harvesting IoT

3.1 System model

We consider a multi-hop relay based WSN architecture that consists of N sensors and a sink node. Each sensor node works as both a data conveyor (relay) and an energy transmitter to enable T-SWIPT technique in the network. These sensor nodes are homogeneous in terms of sensing, computation and transmission, and have a single antenna. The sink serves as a central controller and handles all the routing and signaling issues. The sink node has not only obligation for gathering data from all the sensors but also broadcast energy to all sensors. The network is termed as a directed graph $G = (v, e)$, where the set of vertices v, represents the sensors, and e indicates the set of edges. A directed link

$(i, j) \in e$ exists if $v_{ij} < u_{tx}$ where v_{ij} signifies the interspace between sensor i and sensor j and u_{tx} represents the range of transmission of sensor nodes. The transmission range of sensors u_{tx} changes with the transmission power of sensor nodes i.e. u_{tx} varies along sensor nodes. We suppose that the channel follows a quasi-static block-fading model with Rayleigh distribution between the transmitting and the receiving node [13, 29]. However, it is possible to use other channel fading models also, such as Nakagami, Rice, etc. In this paper, we consider imperfect channel state information (CSI) (due to noisy channel) motivated by the prior researches [32-33]. The receiver end able to calculate the distribution of CSI by the received signal and finally transmitted as feedback to transmitter. Thus, both the transmitter and receiver have information about channel gain. Further, RF signal received by the receiver is corrupted by an additive white Gaussian noise (AWGN) of receiver's antenna and received aggregated co-channel interference because of sharing the same frequency band at same transmission slot.

3.2 T-SWIPT Technique

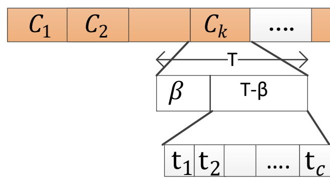

Fig.2. Time slot (T) assignment

Sink collects the information from sensor nodes dispersed in monitoring area in collection period $(C_1, C_2, \ldots C_k, \ldots)$. Moreover, each collection period has equal time duration $(|C_1| = |C_2| = |C_k| = T)$. The information collection period (T) is divided into two time slots including energy broadcast slot of duration β from sink, and data transmission slot of duration $(T - \beta)$ for the sensor nodes. Further, data transmission slot is divided into c number of different data transmission time slot having equal time duration $(|t_c| = |t_2| \ldots\ldots = |t_c| = t)$ among N sensors to transmit data; such that it holds the inequality $\beta + ct \leq T$. It means that maximum c number of nodes transmit data simultaneously. In order to avoid collisions due to data transmission and enhance energy efficiency, we use the scheduling algorithm proposed in [34] for data collection schedule among sensors. If we use conflict free schedule then each sensor node requires its own data transmission slot i.e. $c = N$.

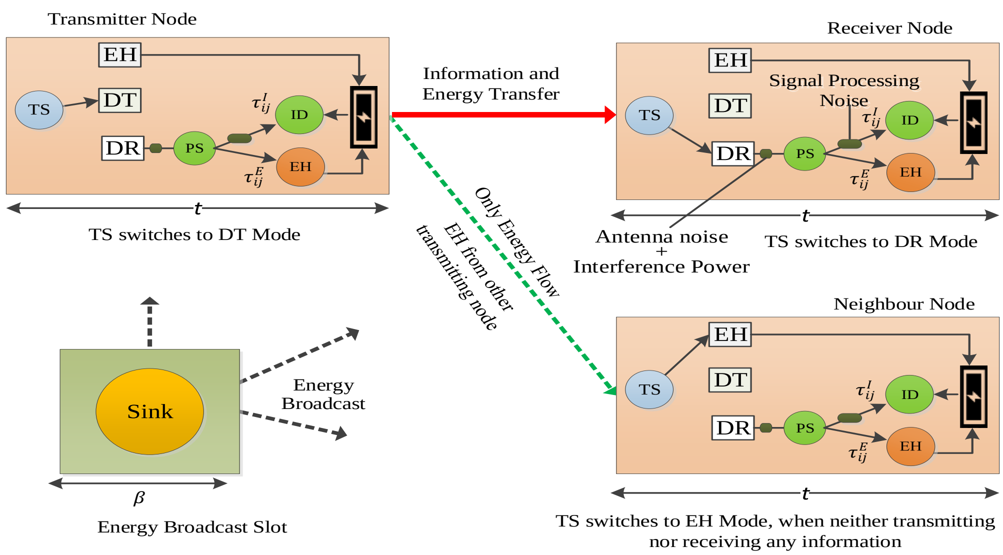

Fig. 3. Technical architecture of T-SWIPT

A Sensor node is comprised of an energy harvesting unit, a power splitting unit, a traditional signal processing unit, time switching unit and a rechargeable battery. Because of some hardware constraints [35], the circuit employed for data processing in the receiving sensor cannot attach with the energy harvesting circuit in practical operation. Hence, the ID unit is separated from the EH unit. Here, we neglect the noise and power loss created by the power splitting unit and time switching unit in signal processing. In addition, P_c is the constant power consumption for overall data sensing and processing in time slot T for all sensors. As, data receiving require less amount of energy than data transmission. We neglect the energy consumption in data receiving by sensors. The advantage of the proposed T-SWIPT technique is that sensor node harvests energy in three ways- (i) from sink; (ii) from received RF signal (using PS protocol); (iii) from neighboring data transmitting node, overall more harvested energy improves the network efficiency.

In any time slot t, multiple sensors send their information to receiver as long as these signals are orthogonal to each other. Hence, it is plausible to have more than one sensor to send sensed information in the same transmitting slot so long as they do not clash with one another. Synchronization between transmission slots of multiples nodes in distributed sensor environment achieved by reference broadcast synchronization protocol [36]. Sink broadcasts reference beacon packet at the beginning of β time slot and the sensor nodes switch to information decoding mode to decode the reference beacon packet and put its arrival time as timestamp for comparing their clocks. To achieve synchronization, in data transmission slot, these receivers exchange their timestamp of beacon packet to calculate their relative phase offset.

Without loss of generality, we consider three sensor nodes (transmitter, receiver and neighbor) and one sink to show the working idea of T-SWIPT technique as shown in the Fig. 3. In time slot t, a node can work in any one of the three-operation mode (EH/DT/DR). The working steps are as follows:

1) In β time slot, sink node broadcasts the energy signal (shown as dotted green arrow in the Fig. 3), and all three sensors harvest energy simultaneously and accumulate it into their rechargeable batteries.
2) In t time slot, for transmitter node (i) , time switcher switches in DT mode, to enable RF signal transmission to the intended receiver (j) carrying both information and energy simultaneously as shown in the Fig. 3 as solid red arrow, and in the meantime only energy flows to other neighbour node (unintended receivers) as shown in the Fig. 3 as dotted green arrow.
3) Meanwhile in the same time slot t, the receiver's time switcher switches to DR mode and the received RF signal is given to power splitter circuit, where it splits the received signal into ratio $\tau_{ij}^{I}$and τ_{ij}^{E} signals for simultaneous ID and EH respectively, where $0 \leq \tau_{ij}^{I} \leq 1$ and $0 \leq \tau_{ij}^{E} \leq 1$ such that $\tau_{ij}^{I} + \tau_{ij}^{E} \leq 1$ defined in section 4.1 as optimization problem constraint A7 . The harvested energy stored into the rechargeable battery for later use in forwarding the data.
4) In addition, meanwhile (in the same t slot) the neighbour sensor node that is neither transmitting nor receiving any intended information, its switcher switches to EH mode and only harvest energy from ambient RF signals transmitted in its surroundings environment (unintended transmitters) regardless of sink. The harvested energy stored into the rechargeable battery for later use in forwarding the data.

The working steps as flow chart of the proposed T-SWIPT technique is presented in the Fig. 4. First the operation in β slot takes place, where all sensors simultaneously harvest energy from the sink broadcast energy. After that, transmitters, receivers and other nodes work parallel in any particular slot t. Let us assume a binary indicator a_{ij}, such that $a_{ij} = 1$ if sensor j cannot harvest power from sensor i (neighbor sensor, unintended transmitter). When sensor i is conveying sensed information to its intended receiver (not sensor j) in an information transmission slot, it means that sensor j is itself either sending information to its intended receiver or receiving information from its other intended transmitter in the same transmission slot. It is to be noted that $a_{ii} = 1$.

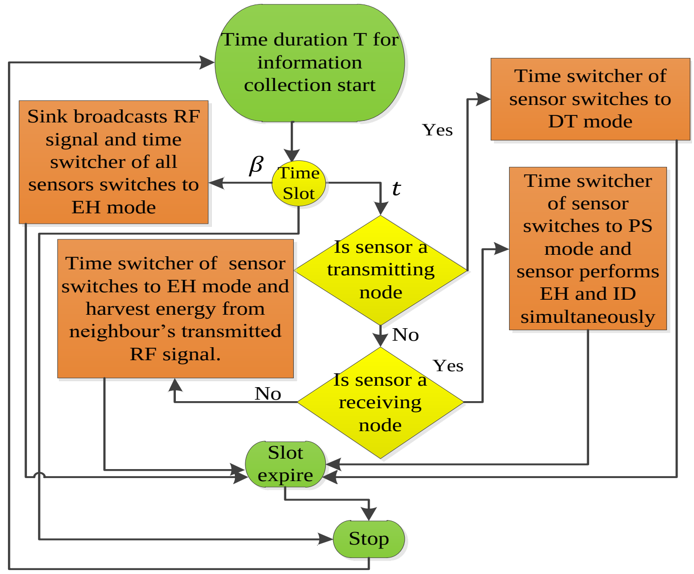

Fig. 4. Working of T-SWIPT technique

The incident RF signal power is absorbed by effective area of antenna and rectified with energy conversion efficiency, and converted into output DC (direct current) power (transmission power). The output DC power of senor node depends upon RF-to-DC conversion efficiency coefficient η_{ij} as dictated by non-linear EH model [37]. The energy conversion coefficient η_{ij} increases with the increment in incident RF signal power until it reaches to saturation point i.e. ${\eta_{ij}}^{max} = 0.8$ [38]. Then further increase in the input power RF signal has no effect on η_{ij} . Whereas, initially the transmission power (output DC power) of node also increases with the increment of η_{ij} and reaches to maximum transmission power when η_{ij} becomes stable. The maximum transmission power P_{max} is also restricted due to hardware constraint limitation, which is dictated as constraint (A3) in section 4.1. And, also the EH circuit triggers the RF-to-DC conversion only if incident input RF signal power is greater than minimum required power P_{min}, which is also dictated as constraint (A3) in section 4.1. As, our objective is to maximize the energy efficiency of the network, i.e. achieving the higher data rate and harvested energy from the same received RF signal power. So, there is a tradeoff between power splitting ratio and transmit power P_{ij}.

Based on the proposed T-SWIPT technique, we compute the total energy harvested by all the sensors in the network analytically. The maximal energy harvested in time T by receiving node j from transmitting node i, denoted by E_D, in Joule, given as:

$$E_D = \sum_{i=1}^{d} P_{ij}\varepsilon_j \eta_{ij}\tau_{ij}^{E} g_{ij} t \quad , d \in N, \tag{1}$$

where, d is the set of transmitting sensor node which uses node j as relay, P_{ij} denotes the power used by transmitter i to transmit data to receiver j (input incident RF signal power at receiver j), g_{ij} represents the power gain of channel, $0 < \varepsilon_j < 1$ is the energy harvesting coefficient for node j from node i, which indicates that receiver j doesn't harvest all of the power emitted by node i. The reason behind it is that other sensors also harvest power from the transmitting node likewise the neighbor node, because of the fact that signal dissemination by non-directional antennas is ambient. η_{ij} represents energy conversion efficiency to convert the received RF signal power to output power such as, $0 < \eta_{ij} < 1$, so it can be stored for later use, which depends on the energy harvesting circuitry and the process of rectification.

Similarly, let E_I represents the quantity of harvested energy by receiving node j from antenna noise and co-channel interference signal in data gathering time T as:

$$E_I = \sum_{i=1}^{d} (\sigma_{I,ij}^2 + \sigma_{A,ij}^2)\eta_{ij}\tau_{ij}^{E} t, \tag{2}$$

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where $\sigma^2_{A,ij}$ stand for AWGN powers emerging from the receiver j antenna, $\sigma^2_{I,ij}$ represents the power of total co-channel interference received by receiver j.

Similarly, let E_S represents the quantity of energy harvested by receiving node j from the broadcasted power P_s through sink node in β time slot given as:

$$E_S = P_s \varepsilon_j \eta_{ij} g_{ij} \beta \tag{3}$$

Similarly, let E_O is the harvested energy by sensor j (neither transmitting nor receiving node) from other 'm' unintended transmitting neighboring nodes in data gathering period T given as:

$$E_O = \sum_{i=1}^{m} P_{ij} \varepsilon_j \eta_{ij} g_{ij}\, t(1 - a_{ij}), \qquad m \in N \tag{4}$$

Thus, the total energy harvested by the receiver sensor j in an information gathering time T calculated as:

$$E^j_{TH} = E_D + E_I + E_S + E_O \tag{5}$$

The aggregate power depletion of the network system is used in optimization problem, which is the primary objective of this paper. In particular, the energy depletion of the network system E_{TC} can be given as:

$$E_{TC} = P_c T + \sum_{i,j=1}^{N} \mu P_{ij} t - \sum_{j=1}^{N} E^j_{TH} \tag{6}$$

The first term in Eq. (6), i.e., $P_c T$ is the total fixed power depleted by the all sensors to sense and gather information in the network during T independent of harvested energy, the second term is the total energy depletion in the transmitter's power amplifier, where $\mu \geq 1$ denotes inefficacy of the transmitter's power amplifier. The total harvested energy E^j_{TH} interpreted as remuneration energy of the network system.

4. Energy Efficiency Optimization of T-SWIPT

In this section, we formulate an optimization problem in terms of energy efficiency and present its solution using Lagrangian optimization method. The energy efficiency of the network depends on data rate to the total power consumption. If we increase the β time slot then energy harvesting duration increases, and data rate of the system decreases on lower transmitting power (P_{ij}). The data rate also depends upon ID ratio τ^I_{ij} of PS protocol, if lower τ^I_{ij} is used then there is a further decrease in data rate. Whereas, lower value of β, and higher value of τ^I_{ij} increases the data rate on increasing transmitting power but lower down the energy harvesting duration. Therefore, overall energy efficiency of the network is not maximized because there is coupling of β, τ_{ij} and P_{ij}. For optimal energy efficiency of the network, above parameters needs to be optimized. The received signal power (y) at receiver of received signal (q) with incident power P_{ij} is given as:

$$y = \sqrt{P_{ij}}\, g_{ij} q + n_{a,j} + I_j \tag{7}$$

where, $n_{a,j}$ represents the AWGN due to receiver antenna with zero mean and variance $\sigma^2_{A,i,j}$. I_j represents the received aggregated co-channel interference on receiver's channel with zero mean and variance $\sigma^2_{I,i,j}$. The Shannon's channel capacity between transmitting sensor i and receiving sensor j is given as:

$$X_{ij} = V\, log_2\left(1 + \frac{P_{ij}\tau^I_{ij} g_{ij}}{\tau^I_{ij}\left(\sigma^2_{I,ij} + \sigma^2_{A,ij}\right) + \sigma^2_{S,ij}}\right) \tag{8}$$

where, $\sigma^2_{S,ij}$ represents the noise power generated by processing of signal at receiver j, $\frac{P_{ij}\tau^I_{ij} g_{ij}}{\tau^I_{ij}\left(\sigma^2_{I,ij} + \sigma^2_{A,i,j}\right) + \sigma^2_{S,ij}}$ represents the signal-to-interference-plus-noise ratio (SINR) between transmitting node i and receiving node j, and V denotes bandwidth of channel. The maximal amount of information (data rate) accurately transmitted from transmitting node i to receiving node j in T time slot is given as:

$$D_{ij} = tV\,log_2(1 + \frac{P_{ij}\tau_{ij}^{I} g_{ij}}{\tau_{ij}^{I}\left(\sigma_{I,ij}^{2} + \sigma_{A,ij}^{2}\right) + \sigma_{S,ij}^{2}}), \quad t \leq \frac{T-\beta}{c}, c \in N \tag{9}$$

The total number of bits that is successfully received by sink node (bits/second) is defined as throughput of the network, and it is also valid for any two nodes that are connected and transmit data to each other and is given as:

$$\omega(P, \tau, \beta) = \sum_{i,j=1}^{N} \delta_{ij} D_{ij} \tag{10}$$

where $P = \{P_{ij} \geq 0, \forall i, j \in v\}$ is the transmit power allocation policy, $\tau = \{\tau_{ij}^{I}, \tau_{ij}^{E} \geq 0, \forall i, j \in v\}$ is the policy of power splitting, $\beta > 0$ is the energy broadcast policy. δ_{ij} is a positive weight which denotes priorities of different receiver nodes to attain fairness in the network system and is prescribed by the application layer. The total number of bits received by sink node per Joule consumed energy is interpreted as the average energy efficiency and is given as:

$$\psi\,(P, \tau, \beta) = \frac{\omega(P,\tau,\beta)}{E_{TC}(P,\tau,\beta)} \tag{11}$$

4.1 The Optimization Problem

In the given section, we formulate the maximization problem of average energy efficiency for the T-SWIPT technique as non-linear optimization problem and expressed as:

$$max_{P,\tau,\beta}\ \psi(P, \tau, \beta) \tag{12}$$

subject to- $A1$: $D_{ij} \geq D_{min},\ \forall i, j;$ $A2$: $E_{TH}^{j} \geq E_{min},\ \forall j;$ $A3$: $P_{min} \leq P_{ij} \leq P_{max}, \forall i, j;$ $A4$: $\beta \leq T - ct;$ $A5$: $\tau_{min}^{I} \leq \tau_{ij}^{I} \leq \tau_{max}^{I}$; $A6$: $\tau_{min}^{E} \leq \tau_{ij}^{E} \leq \tau_{max}^{E}$; $A7$: $\tau_{ij}^{I} + \tau_{ij}^{E} \leq 1;$ $A8$: $\beta > 0$,

where A1 specifies that the data rate of transmitted information from node i to node j should be more than or equal to the minimal data rate requirement D_{min}. Although D_{min} is not an optimization variable in this paper, we can balance the energy efficiency of the network by varying the minimum data rate. The minimal EH constraint A2 indicates that the energy harvested from the RF signals must be greater than the minimal harvested energy to trigger the harvesting circuit and avoid temporal death problem [39]. Moreover, minimum transmit power P_{min} is required to satisfy the minimum data rate requirement D_{min}. A3 indicates the transmit power limitation of the transmitting sensor, the value of P_{max} and P_{min} is the upper and lower bound on the power emitted by the transmitting node respectively which is a constant and controlled by the power amplifier's hardware constraints. P_{min} must be greater than zero to avoid the cold-start problem, so that the received RF signal power is enough for both ID and EH. A4 indicates the energy broadcast time constraint, which should be less than or equal to information collection period minus total transmission slot time. Boundary constraints in A5 and A6 denotes the lower bound and upper bound power splitting ratio for ID and EH respectively. This is due to receiver hardware limitation of computing capability. Such that $\tau_{min}^{I} + \tau_{max}^{E} = 1$ and $\tau_{max}^{I} + \tau_{min}^{E} = 1$. In other representation, power splitting ratio for information decoding is denoted as $\tau_{ij} = \tau_{ij}^{I}$ and for energy harvesting $1 - \tau_{ij} = \tau_{ij}^{E}$. Whereas, constraint define in A7 represents that there is no extra power gain during power splitting process asserted as passive sensor node. $A8$ indicates that the energy broadcast time should be greater than zero.

4.2 The Solution

The main problem in the process of finding optimum solution is the absence of convexity in the formulated maximization problem as given in Eq. (12). Because the energy efficiency-maximization problem is the fraction of concave to convex function (for proof see Appendix-A). The denominator of the fractional problem is positive affine function with respect to transmit power for given power splitting ratio and sink broadcast time and *vice-versa*, whereas numerator is the concave function because of coupling in the variables (P, τ, β) under constraint A1, A2, A3 and A4. In addition, the constraints A5 to A8 are integer constraints (Boolean value) and coupled with A2. Generally, we do not have any standard way to solve the non-convex maximization problems. Thus, we instigate an analogous conversion of the objective function so that it can be solved by applying the nonlinear fractional programming method. A similar objective function in form of subtraction is given by transforming the previously given objective function that is in form of fraction so that the problem can be made tractable. ψ^{opt} represents the optimal energy efficiency of the network system and can be given as

$$\psi^{opt} = \frac{\omega(p^{opt},\tau^{opt},\beta^{opt})}{E_{TC}(p^{opt},\tau^{opt},\beta^{opt})} = max_{P,\tau,\beta}\frac{\omega(P,\tau,\beta)}{E_{TC(P,\tau,\beta)}} \quad (13)$$

Now, to optimize the problem in (12), the following fundamental theorem is introduced.

Theorem I. The optimal energy efficiency ψ^{opt} is attained on condition

$$max_{P,\tau,\beta}[\omega(P,\tau,\beta) - \psi^{opt}E_{TC}(P,\tau,\beta)] \quad (14)$$

$$= \omega(p^{opt},\tau^{opt},\beta^{opt}) - \psi^{opt}E_{TC}(p^{opt},\tau^{opt},\beta^{opt}) = 0 \quad (15)$$

for $\omega(P,\tau,\beta) > 0$ *and* $E_{TC}(P,\tau,\beta) > 0$

Now, an algorithm-1 with iterations based on Dinkelbach method is presented, based on an optimum solution found by using the objective function in [40]. It can be seen from the algorithm-1 that in each main loop iteration, the optimization problem in Eq. (16) is solved for given energy efficiency ψ:

$$max_{P,\tau,\beta}[\omega(P,\tau,\beta) - \psi E_{TC}(P,\tau,\beta)] \quad (16)$$

subject to $A1, A2, \dots \dots A8$.

Now, by the following theorem convergence of the algorithm-1 is shown.

Theorem II. The algorithm-1 converges to optimum energy efficiency on the condition that in each iteration, the problem (16) should be solved. Its proof can be found in [20, 40].

To obtain a compliant algorithm for optimizing $\{P,\tau,\beta\}$, the capacity of channel X_{ij} in Eq. (8) can be approximated as:

$$X_{ij} = V\,log_2\Big(\frac{P_{ij}\tau^I_{ij}g_{ij}}{\tau^I_{ij}\left(\sigma^2_{I,ij}+\sigma^2_{A,i,j}\right)+\sigma^2_{S,ij}}\Big) \quad (17)$$

That is a compact approximation for excessive signal-to-interference-plus-noise ratio (SINR). Practically a high SINR ($\frac{P_{ij}\tau^I_{ij}g_{ij}}{\tau^I_{ij}\left(\sigma^2_{I,ij}+\sigma^2_{A,ij}\right)+\sigma^2_{S,ij}} \gg 1$) is needed to assure minimum data rate D_{min} satisfy by the system as quality of service (QoS) and faultless transmission.

Algorithm 1. Lagrangian based optimization algorithm

Input:
I_{max} = upper bound for iteration number;
ɵ = the maximum tolerance;
ψ= energy efficiency;
k= Iteration index;
Output:
$(P^{opt},\tau^{opt},\beta^{opt})$: an optimum strategy for $\{P,\tau,\beta\}$
ψ^{opt}: optimal energy efficiency
1:$k = 1$,$\psi = 0$;
2: Use transmission schedule algorithm [34] for data transmission schedule.
3: while $k \le I_{max}$ do {main loop}
4: For given value of ψ, obtain resource allotment strategies $\{P,\tau,\beta\}$ by solving the optimization problem in (16)
5: if $(\omega(P,\tau,\beta) - \psi E_{TC(P,\tau,\beta)}) <$ ɵ then
6: return $\{P^{opt},\tau^{opt},\beta^{opt}\} = \{P,\tau,\beta\}$ and $\psi^{opt} = \frac{\omega(P,\tau,\beta)}{E_{TC(P,\tau,\beta)}}$
7: else
8: Set $\psi = \frac{\omega(P,\tau,\beta)}{E_{TC(P,\tau,\beta)}}$ and $k = k+1$

9: end if
10: end while

The primal energy efficiency problem in the Eq. (16) is solved through dual decomposition method to obtain an optimal strategy for $\{P, \tau, \beta\}$. Firstly, we require the Lagrangian function to the original maximization problem, which can be achieve by finding product of the Lagrangian multipliers with the associated constraints A1, A2, ... A7 and A8. The partial Lagrangian function of Eq. (16) is given as:

$$L(\psi, \vartheta, \theta, \phi, \gamma, \varphi, \rho, P, \tau, \beta) = \sum_{i,j=1}^{N} \delta_{ij} tV\, log_2\left(\frac{P_{ij}\tau_{ij}g_{ij}}{\tau_{ij}\left(\sigma_{I,ij}^2 + \sigma_{A,ij}^2\right) + \sigma_{S,ij}^2}\right) - \psi\left(P_c T + \sum_{i,j=1}^{N} \mu P_{ij} t - \sum_{j=1}^{N} E_{TH}^{j}\right) + \sum_{i,j=1}^{N} \vartheta_{ij}\left(D_{ij} - D_{min}\right) + \sum_{j=1}^{N} \theta_j\left(E_{TH}^{j} - E_{min}\right) + \sum_{i,j=1}^{N} \phi_{ij}\left(P_{ij} - P_{min}\right) + \sum_{i,j=1}^{N} \gamma_{ij}\left(P_{max} - P_{ij}\right) + \sum_{i,j=1}^{N} \varphi_{ij}\left(\tau_{ij}^{E} + \tau_{ij}^{I} - 1\right) + \rho\left(\frac{T - ct}{\beta} - 1\right) \quad (18)$$

For the associated constraints, the Lagrangian multiplier vector $\boldsymbol{\vartheta} = [\boldsymbol{\vartheta_{ij}}, \boldsymbol{i}, \boldsymbol{j} = \mathbf{1}, \ldots \ldots \boldsymbol{N}]^{\boldsymbol{T}}$ is for QoS requirement related to higher SINR $\left(\frac{P_{ij}\tau_{ij}^{I}g_{ij}}{\tau_{ij}^{I}\left(\sigma_{I,ij}^2+\sigma_{A,ij}^2\right)+\sigma_{S,ij}^2} \gg 1\right)$ of the system in A1. Lagarangian multiplier vector $\boldsymbol{\theta} = [\boldsymbol{\theta_j}, \boldsymbol{j} = \mathbf{1}, \mathbf{2}, \ldots \boldsymbol{N}]^{\boldsymbol{T}}$ corresponds to inequality constraint A2 for minimum harvesting energy to avoid temporal death problem. Lagarangian multiplier vector $\phi = [\boldsymbol{\phi_{i,j}}, \boldsymbol{i}, \boldsymbol{j} = \mathbf{1}, \ldots . \boldsymbol{N}]^{\boldsymbol{T}}$ is for individuals minimum transmit power in constraint A3 to satisfy the minimum data rate of system for QoS. Lagarangian multiplier vector $\boldsymbol{\gamma} = [\boldsymbol{\gamma_{ij}}, \boldsymbol{i}, \boldsymbol{j} = \mathbf{1}, \ldots . \boldsymbol{N}]^{\boldsymbol{T}}$ is for individuals transmit power limited to maximum transmit power (hardware limitation) in constraint A3. Lagarangian multiplier ρ is for balancing the information collection period (T) between sink broadcast duration for EH (β) and total data transmission period (ct) for sensors in constraint A4. The Lagrangian multiplier vector $\boldsymbol{\varphi} = [\boldsymbol{\phi_{i,j}}, \boldsymbol{i}, \boldsymbol{j} = \mathbf{1}, \ldots . \boldsymbol{N}]^{\boldsymbol{T}}$ for power splitting ratio constraint A7 . On the other hand, A5, A6 and A8 are the boundary condition constraints in integer form, which makes the maximization problem as non-linear maximization problem due to coupling of variable (P, τ, β) in constraints A1, A2, A3, A4 and A7. To find the solution of maximization problem, we relax the integer constraints A5 and A6 into real value between $0 \leq \tau_{ij}^{I} \leq 1$ and $0 \leq \tau_{ij}^{E} \leq 1$ and A8: $\beta > 0$ in time-sharing manner that is caught through the Karush-Kuhn-Tucker (KKT) conditions. We use these non-negative constraints A5, A6 and A8 to find the solution of Lagarangian multiplier function in successive iteration.

4.2.1 Dual Decomposition method

By using the method of duality, the dual problem of the original problem in Eq. (16) is given by

$$min_{\vartheta,\theta,\phi,\gamma,\varphi,\rho>0}\, max_{P,\tau,\beta} L(\psi, \vartheta, \theta, \phi, \gamma, \varphi, \rho, P, \tau, \beta) \quad (19)$$

By using Lagrange dual decomposition the optimum strategy for $\{P, \tau, \beta\}$ is obtained. Precisely, the method of Lagrange dual decomposition is applied to fragment the dual problem in Eq. (19) into a two-level hierarchy. The inner maximization in Eq. (19) is the first level, which is divided into three separate sub-problems at the network's physical layer: (i) transmission power assignment; (ii) power splitting ratio; and (iii) energy broadcast time slot, and solved simultaneously. The outer minimization is the second level, which predominantly upgrades the Lagrangian multipliers. We can iteratively solve the dual problem. Precisely, for a definite value of Lagrange multipliers, sub problems are solved in each main loop iteration by using the KKT conditions. We use the sub gradient technique to upgrade the Lagrange multipliers by using the solutions of the sub problems.

4.2.1.1 First level (Sub problem Solution)

In this level, first order partial differentiation is used in three different sub-problems to find the optimal solution for transmission power assignment, power-splitting ratio and energy broadcast time slot of sink using KKT conditions under constrains A5 A6 and A8, since the optimization variables $(P, \tau, \beta\ )$ are positive.

(i) Transmit power assignment (P_{ij}) - For the given value of τ_{ij} and β , the optimum policy for transmit power assignment is calculated by obtaining first order partial derivative of inner maximization Lagrangian problem with respect to transmit power P_{ij} and equate it to zero as follow:

$$\frac{\partial L}{\partial P_{ij}} = \phi_{ij} - \gamma_{ij} - \mu t\psi + \frac{(Vt\delta_{ij})}{(P_{ij}\log 2)} + \frac{\vartheta_{ij}VT}{P_{ij}\log 2} + (\theta_j + \psi)(1 - a_{ij})m\varepsilon_j g_{ij}\eta_{ij}t - (\theta_j + \psi)d\varepsilon_j g_{ij}\eta_{ij}t(1 - \tau_{ij}), \quad \forall i,j \in N \tag{20}$$

Now, after solving the Eq. (20) for P_{ij} by equating $\frac{\partial L}{\partial P_{ij}} = 0$, we get the solution for optimal transmit power assignment as:

$$P_{ij} = \left(\frac{Vt}{\log 2}(\vartheta_{ij} + \delta_{ij})\right)/(\gamma_{ij} - \phi_{ij} + \mu t\psi - m\varepsilon_j g_{ij}\eta_{ij}t(1 - a_{ij})(\theta_j + \psi) - d\varepsilon_j g_{ij}\eta_{ij}t(1 - \tau_{ij})\ (\theta_j + \psi) \tag{21}$$

(ii) Power spitting ratio (τ_{ij}) – For the given value of transmit power P_{ij} and energy broadcast time slot of sink β, the optimal power-splitting ratio is calculated by obtaining first order partial derivative of inner maximization Lagrangian problem with respect to τ_{ij} and equate it to zero as follow:

$$\frac{\partial L}{\partial \tau_{ij}} = (\vartheta_{ij}Vt(\sigma_{S,i,j}^2 + \tau_{ij}(\sigma_{I,i,j}^2 + \sigma_{A,i,j}^2))((P_{ij}g_{ij})/(\sigma_{S,i,j}^2 + \tau_{ij}(\sigma_{I,i,j}^2 + \sigma_{A,i,j}^2)) - (\tau_{ij}g_{ij}(\sigma_{I,i,j}^2 + \sigma_{A,i,j}^2))/(\sigma_{S,i,j}^2 + \tau_{ij}(\sigma_{I,i,j}^2 + \sigma_{A,i,j}^2)^2))/(\tau_{ij}P_{ij}g_{ij}\log 2) - \sigma_{I,i,j}^2 d\eta_{ij}t\psi - (\theta_j + \psi)P_{ij}d\varepsilon_j\eta_{ij}g_{ij}t - \theta_j\sigma_{I,i,j}^2 d\eta_{ij}t + (Vt\delta_{ij}(\sigma_{S,i,j}^2 + \tau_{ij}(\sigma_{I,i,j}^2 + \sigma_{A,i,j}^2)) * \left(\frac{P_{ij}g_{ij}}{\sigma_{S,i,j}^2 + \tau_{ij}(\sigma_{I,i,j}^2 + \sigma_{A,i,j}^2)} - (\tau_{ij}P_{ij}g_{ij}(\sigma_{I,i,j}^2 + \sigma_{A,i,j}^2))/(\sigma_{S,i,j}^2 + \tau_{ij}(\sigma_{I,i,j}^2 + \sigma_{A,i,j}^2)^2)\right)/(\tau_{ij}P_{ij}g_{ij}\log 2), \ \forall i,j \in N \tag{22}$$

Now, after solving the Eq. (22) for τ_{ij} by equating $\frac{\partial L}{\partial \tau_{ij}} = 0$ we get the solution for optimal power-splitting ratio as expressed in Eq. (23).

$$\tau_{ij} = -(\log 2\ \ d\theta_j\sigma_{I,i,j}^2\sigma_{S,i,j}^2\eta_{ij} - \left(\sqrt{\log 2\ \ d\sigma_{S,i,j}^2\eta_{ij}(\theta_j + \psi)(\sigma_{I,i,j}^2 + P_{ij}\varepsilon_j g_{ij})} \times \sqrt{\begin{matrix}((\vartheta_{ij} + \delta_{ij})(\sigma_{I,i,j}^2 + \sigma_{A,i,j}^2)4V) + (\log 2\ \ d\sigma_{S,i,j}^2\sigma_{I,i,j}^2\eta_{ij}(\theta_j + \psi)) + \\ \left(\log 2\ \ dP_{ij}\sigma_{S,i,j}^2\varepsilon_j\eta_{ij}g_{ij}(\theta_j + \psi)\right)\end{matrix}}\right) + \log 2\ d\sigma_{I,i,j}^2, \sigma_{S,i,j}^2\eta_{ij}\psi + \log 2\ dP_{ij}\sigma_{S,i,j}^2\varepsilon_j\eta_{ij}g_{ij}(\theta_j + \psi))/(2(\log 2\ d(\sigma_{I,i,j}^2 + \sigma_{A,i,j}^2)\sigma_{I,i,j}^2\eta_{ij}(\theta_j + \psi) + \log 2\ d(\sigma_{I,i,j}^2 + \sigma_{A,i,j}^2)P_{ij}\varepsilon_j\eta_{ij}g_{ij}(\theta_j + \psi))) \tag{23}$$

(iii) Energy broadcast time slot for sink (β) - For fixed transmit power P_{ij} and power splitting ratio τ_{ij} of sensor node, the optimal policy for energy broadcast time slot is calculated as follow:

$$\frac{\partial L}{\partial \beta} = \theta_j P_s\varepsilon_j\eta_{ij}g_{ij} - \frac{\rho(T - ct)}{\beta^2} + P_s\varepsilon_j\eta_{ij}g_{ij}\psi \tag{24}$$

Now, after solving the Eq. (24) for β by equating $\frac{\partial L}{\partial \beta}$ to zero, we get the solution for optimal energy broadcast time slot β as:

$$\beta = \sqrt{\frac{\rho(T - ct)}{P_s\varepsilon_j\eta_{ij}g_{ij}(\theta_j + \psi)}} \tag{25}$$

4.2.1.2 Second level (Master problem Solution)

Here, we apply the sub-gradient technique to get a solution for the outer minimization problem in (19). In other words, to obtain Lagrange multipliers ϑ_{ij},$\theta_j, \phi_{ij}, \gamma_{ij}, \varphi_{ij}$ and ρ for a given values of $P_{ij}, \tau_{ij}$and β. Sensor node j upgrades its Lagrangian multipliers at iteration x as follows:

$$\vartheta_{ij}(x+1) = [\vartheta_{ij}(x) + \delta(x)(D_{ij} - D_{min})]^+, \quad (26)$$

$$\theta_j(x+1) = [\theta_j(x) + \delta(x)(E_{TH}^j - E_{min})]^+, \quad (27)$$

$$\phi_{ij}(x+1) = [\phi_{ij}(x) + \delta(x(P_{ij} - P_{min})]^+, \quad (28)$$

$$\gamma_{ij}(x+1) = [\gamma_{ij}(x) + \delta(x)(P_{max} - P_{ij})]^+, \quad (29)$$

$$\varphi_{ij}(x+1) = [\varphi_{ij}(x) + \delta(x)(\tau_{ij}^E + \tau_{ij}^I - 1)]^+, \quad (30)$$

$$\rho(x+1) = [\rho(x) + \delta(x)(\frac{T-ct}{\beta} - 1)]^+, \quad (31)$$

where, $x \geq 0$ is the index for iteration, $\delta(x)$ is the positive step size for each iteration. The upgraded Lagrange multipliers in (26), (27), (28), (29), (30) and (31) can be utilized for upgrading the strategies for resource allotment in (21), (23) and (25) by finding solution of the sub problems in (19). For the reason that the approximated objective function of the original problem is concave w. r. t the maximization variables P_{ij}, τ_{ij} and β, it is promised that the original optimum solution can be attained by solving the problem in first level and second level iteratively until convergence is achieved on the condition that the selected step size, $\delta(x)$, is small enough. The convergence of the iterative algorithm depends upon obtaining zero duality gap between approximated maximization problem and original maximization problem i.e.$(\omega(P, \tau, \beta) - \psi E_{TC(P,\tau,\beta)}) < \theta$).

4.2.2 Complexity Analysis

Now, the time complexity of the proposed Algorithm-1 is analyzed. In step-2, linear time complexity is needed to compute transmission schedule, i.e., $O(c)$. Step-3 composed of two nested loops, outer loop runs for maximum I_{max} number of iteration to update the parameter ψ (P, τ, β) through step-8. The inner loop runs to solve the maximization problem, which is a convex problem as defined in Eq.16. It requires only linear time complexity $O(c)$. Thus, the proposed algorithm has time complexity of $O(c) + O(I_{max}c) = O(I_{max}c)$, which is a polynomial time complexity. In worst case, if there is separate transmission slot for each node, then $c = N$.

5. Simulation and Results

In the given section, simulations are performed to evaluate the performance of the proposed T-SWIPT technique for relay-based energy harvesting IoT system, focusing on environment setting, performance metrics and comparative analysis of the results.

5.1 Simulation Scenario

The performance evaluation of the proposed T-SWIPT technique is presented to show the significant effect towards energy efficiency and system throughput using MATLAB R2017a as simulation tool. The MATLAB functions used in the simulations are-NetArch(length, width, sink-location, initial energy) for creating network architecture with given parameters, NodeArch(NetArch, number of nodes) for distribution of nodes. For distribution of initial energy to each node and to keep track of total energy consumption of the network, first order radio energy model is used. Moreover, SUPR EH model is used as EH model. We consider that 60 sensors are uniformly deployed over $100 \times 100\ m^2$ area. Similar initial energy $2\ mJ$ is provided to all the sensors in their rechargeable batteries. We also consider that all the receiving sensors have similar priority $\delta_{ij} = 1, \forall i, j \in v$, for displaying maximum reachable system energy efficiency. Here we assume that the communication channel experiences Rayleigh flat fading (small-scale fading). In the result, we consider the main loop iterations (I_{max}) in the Dinkelbach method as the total number of iterations, but not for the gradient method. Moreover, for fast convergence, the step size of three sub-problems in Lagrange multiplier is updated through backtracking line search. The maximum allowance transmit power P_{max} taken in each case separately

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for simulating results. The minimum harvest energy is set to be 10% of P_{max}. The maximum energy conversion efficiency $\eta_{ij}{}^{max}$ is about to 80% taken for practical wireless IoT network [38]. The corresponding simulation parameters are provided in Table 2.

Table 2. Simulation Parameters

Parameter	Value	Parameter	Value
g_{ij}	1	ε_j	1
τ_{ij}	$[0.2, 0.4, 0.6, 0.8]$	d	5
T	$30\ sec,$	P_c	$0.001W$
P_s	$[0.01, 0.04, 0.06, 0.08,]W$	μ	1
t	1 sec.	m	5
V	$10^3\ Hz$	D_{min}	$200\ bps$
$\sigma^2_{I,i,j}$	$[0, 5, 10, 15]dBm$	c	25
$\sigma^2_{A,i,j}$	$-10\ dBm$	P_{min}	$0.005\ W$
$\sigma^2_{S,i,j}$	$-10\ dBm$		

5.2 Result Analysis

This section is divided into three subsections to show the effectiveness of the proposed T-SWIPT technique. (i) Convergence analysis; (ii) Performance test; (iii) Comparison with respect to state-of-the-art algorithms; (iv) Network wide performance.

5.2.1 Convergence Analysis

This subsection analyzes the convergence rate of the proposed algorithm-1 with respect to number of iteration over maximum allowance transmit power of sensors and power spitting ratio in the Fig. 5 and Fig. 6 respectively. The convergent rate of the iterative algorithm defines its effectiveness.

From the Fig. 5, it is evident from the outcomes that as the iteration number increases, there is increase in network energy efficiency and then it converges within 5 iterations in every considered situation. This is because the presented algorithm balances the power-splitting ratio for energy harvesting and information decoding using Lagrangian algorithm to achieve optimal solution. It further shows that the energy efficiency of the system increases with the increase in the value of maximum transmit power, such that $P_{max}(W) = \{0.01, 0.015, 0.02, 0.03\}$. The reason behind is higher transmit power allowance makes the sensor nodes to increase their transmit power, which enhances the SINR at the receiving node, because of which data rate capacity and harvested energy increases, which is ultimately responsible for higher energy efficiency.

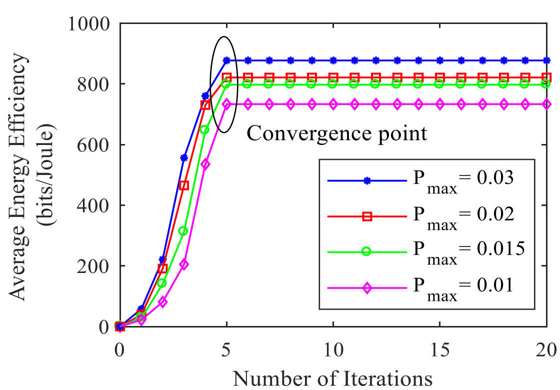

Fig. 5. Average energy efficiency of the system with increasing iterations and varying maximum transmit power P_{max}

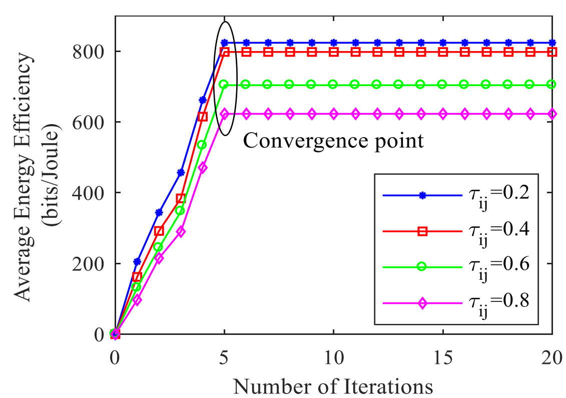

Fig. 6. Average energy efficiency of the system with increasing iterations and varying information decoding power-splitting ratio τ_{ij}

Fig. 6 shows that as the iteration number increases, there is increase in the network energy efficiency and then it converges within 5 iterations in every considered situation under maximum transmit power allowance region $P_{max}(W) = 0.03$. It further shows that the energy efficiency of the system decreases with increase in the value of information decoding power splitting ratio $\tau_{ij} = \tau^I_{ij} \in$

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$\{0.2, 0.4, 0.6, 0.8\}$ for higher value of maximum transmit power allowance region. The reason behind is when value of information decoding ratio τ_{ij} is less; a smaller proportion of the received power is provided to the system for ID and greater part of the power acquired for EH. Higher energy harvesting allows the sensors to transmit more information to the next hop node towards the destination with high power RF signal. Moreover, it is able to compensate the power loss due to transmission of more number of bits and interference. It improves the SINR at the receiver until the channel capacity (data rate) saturated in interference-limited regime, after that energy efficiency becomes independent of ID power splitting ratio and now it depends upon energy harvesting capacity of node. Thus, higher power splitting ratio for energy harvesting ultimately improves the energy efficiency of the overall system until the channel capacity is stable. We consider the minimum information decoding ratio $\tau_{ij}^{I} = 0.2$ to meet the constraint A1: $D_{ij} \geq D_{min}$. When $\tau_{ij}^{I} = 0.1$, receiver is not able to decode enough information successfully (lower SINR value) and fails to keep the constraint $A1$, and then higher harvested energy is of no use if receiver does not received any useful information. Therefore, overall energy efficiency of the system is very low. For the next simulation results, maximum number of iteration is set to be five.

5.2.2 Performance Test

This subsection simulates the average energy efficiency; average throughput and average energy harvested of the proposed algorithm with respect to maximum allowance transmit power of sensors over different value of inference level in the following Fig. 7 to Fig. 9. In addition, the system average energy efficiency with respect to broadcast time slot of sink is also simulated against different transmit power of sink in the Fig. 10.

Fig. 7 shows that the average energy efficiency of the system is a monotonically increasing function of maximum transmit power allowance P_{max}. The energy efficiency of the system quickly improves with increase in maximum transmit power allowance because the larger value of transmit power improves the SINR at the receiver, and also makes the sensors to harvest more energy and use that energy to transmit the information to the next hop node towards the destination with high transmit power. Further, the energy efficiency of the system increases, and reaches the optimal value and keeps stable when ($P_{max} > 0.03\ W$). The reason behind is the algorithm-1 achieves a tradeoff among the power utilization, the system energy efficiency and the average energy harvesting of the system. When the energy efficiency of the system reaches its optimal value, an additional increase in the value of transmission power would degrade the efficiency of the system because of high-energy consumption of the energy-limited sensors. It is also analyzed that even though the interference signals work as a good source of harvesting energy for the system, but not able to help in increasing the energy efficiency at all, because the received power is used to compensate the power consumption due to strong co-channel interference between the nodes and does not provide extra gain in data rate. Therefore, the energy efficiency of the system decreases.

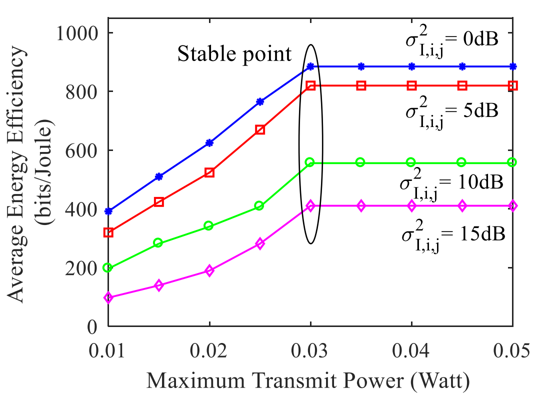

Fig. 7. Average energy efficiency of the system with increasing maximum transmit power P_{max}, and varying interference power $\sigma_{I,i,j}^{2}$

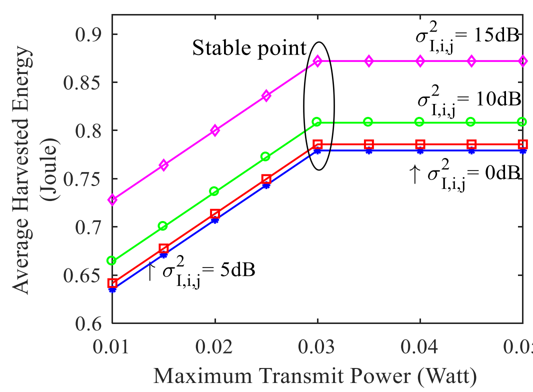

Fig. 8. Average harvested energy of the system with increasing maximum transmit power P_{max}, varying interference power $\sigma_{I,i,j}^{2}$

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restrict the receiver to split the received signal simultaneously for information decoding and harvesting energy, which reduces the energy efficiency of the system. In contrast, for higher maximum transmit

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power P_{max} region, it allow the receiving sensor to split the desired signal in large fraction for EH until the quantity of average harvested energy is stable. Because for high allowance of transmit power, receiver has enough received signal power for simultaneous ID and EH. As soon as the minimum required energy harvesting constraint at the receiver and minimum system data rate constraint are satisfied $A2$: $E_{TH}^{j} \geq E_{min}$, $\forall j$ and $A1$: $D_{ij} \geq D_{min}$, $\forall i, j$; , the transmitting sensors becomes saturated at $\mathrm{P_{max}} = 0.03$ W, to increase the value of transmission power for maximization of energy efficiency. In addition, the output transmit power depends upon energy conversion coefficient as well, which limit the output transmit power up to maximum level as dictated by non-linear EH model. For the above reasons, further increase in the maximum allowance transmit power ($\mathrm{P_{max}} > 0.03$ W) does not increase EH capacity saturation of receiver. Moreover, increasing the value of $\sigma_{I,i,j}^2$, additionally turns out to be a viable energy harvesting source for the receiving node. However, it does not increase the energy efficiency of the system because aggregated co-channel interference impairs the channel and further harvested energy is not enough to compensate the data rate loss. Overall, the system energy efficiency is enhanced through harvesting more energy, when the receiving sensor split large fraction of received power for harvesting energy.

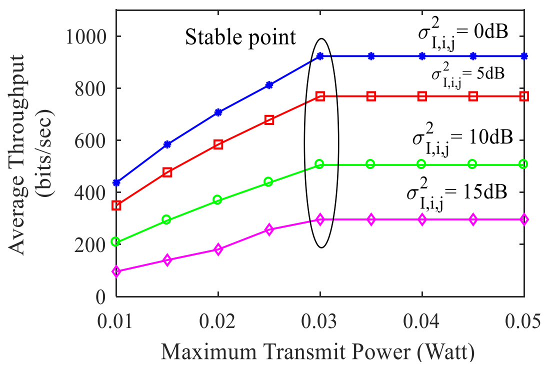

Fig. 9. Average throughput of the system with increasing maximum transmit power P_{max}, and varying interference power $\sigma_{I,i,j}^2$

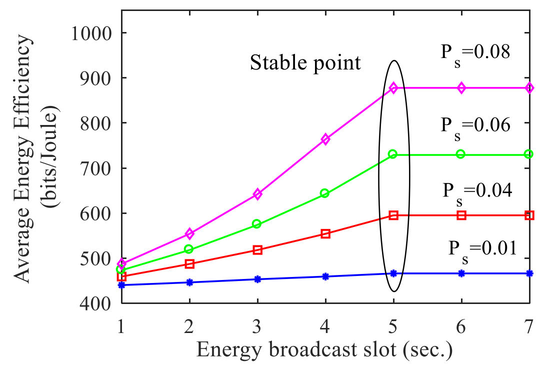

Fig. 10. Average energy efficiency of the system with increasing energy broadcast slot β, and varying sink broadcasting power $\mathrm{P_s}$.

Fig. 9 depicts that the average system throughput is a monotonically non-decreasing function of maximum transmit power allowance P_{max}, for different value of interference power $\sigma_{I,ij}^2$. Larger value of transmit power increases the SINR value at the receiver, it allows the receiver to simultaneously decode the received information signal correctly and harvest more energy in balanced power splitting ratio, which ultimately enhances the overall throughput of the system. The throughput of the system reaches its optimal value and becomes saturated when maximum allowed transmit power reaches to $P_{max} = 0.03W$. Indeed, the transmit power P_{ij} cannot increase further with respect to increasing maximum allowance transmit power P_{max} if the sensor is not able to handle the energy consumption due to higher transmit power in the network. Thus, intensifying the value of the maximum transmit power after a certain value cannot enhance the throughput of the system. Further, it is analyzed that even though the signals of interference can be a valid source for harvesting energy in the system, but high interference decreases the throughput of the system. This is because received signals are corrupted from the higher aggregated co-channel interference from its other transmitting neighboring node and the number of bits cannot be decoded correctly by the receiver due to low value of SINR.

Fig. 10 shows that with increase in broadcast time of sink and transmit power of sink, the average energy efficiency of the network increases because for larger value of β and P_s , more energy would be harvested by the sensors from sink. Further, higher energy harvesting allows the sensors to transmit the information to the next hop node towards the destination with powerful signal. It improves the SINR at the receiver and the node is able to correctly decode the information signal, which ultimately improves the energy efficiency of the overall system. The energy efficiency of the system reaches its optimal value and stays saturated when $\beta > 5\ sec$. The reason behind it is that the given algorithm attains a balance between the energy harvesting time and data gathering time by sink in order to maximize the average energy efficiency of the system.

5.2.3 Comparison with Respect to the State-of-the-Art Algorithms

In this section, T-SWIPT technique is compared with TS driven SWIPT scheme (energy efficiency optimization (EE-TS) [16]) and PS driven SWIPT scheme (orthogonal frequency division multiple access based network system (OFDMA) [18]) in terms of energy efficiency, throughput and harvested energy of the system.

Fig. 11 shows that throughput of the system increases as the SINR value at the receiver increases in each of the schemes. Because high SINR value denotes the fairness in received signal, so possibility of decoding the data correctly increases. However, after a certain value of SINR (18 dB) throughput of T-SWIPT system becomes stable; this is because of limited computation capability and harvested energy of sensors. The reason for system throughput becomes stable is twofold, (i) it fulfilled the constraint A1 and A2; (ii) it also validates the increasing transmission power restriction of non-linear EH, that means the output power of EH circuit is limited by the factor of energy conversion efficiency coefficient. T-SWIPT enabled system turns out to be best in terms of throughput, because node harvests higher amount of energy from both its intended received signal and other unintended transmitting signals in different time slot using time switcher. Whereas OFDMA (PS) or EE-TS scheme harvest energy from the intended received RF signal only. Further, in T-SWIPT scheme node transmit data with high power signal, which increases the SINR value at receiver side that enables the receiver to correctly decode more amounts of data in limited time.

Furthermore, in EE-TS scheme system throughput is better than OFDMA (PS) scheme because TS scheme mainly focus on maximizing the transmit power of node in order to increase system throughput whereas OFDMA (PS) allocates the transmit power to node for fulfilling the minimum data rate in delay–constraint network. And also, in TS-scheme node harvests energy from complete signal rather than fraction of received signal as in OFDMS (PS) that helps node to transmit data in EE-TS scheme with more powerful signal towards receiver node. Therefore, the receiver node experiences high SINR value in EE-TS scheme than SINR value received by receiver node in OFDMA (PS) scheme. This helps in decoding more data correctly in EE-TS scheme than OFDMA (PS) scheme. Therefore, TS scheme has better system throughput than PS scheme. Overall, T-SWIPT improves the average system throughput by 29% and 66 % over EE-TS and OFDMA (PS) scheme respectively at the stable point.

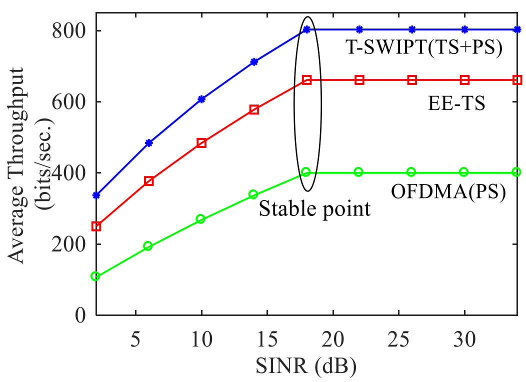

Fig. 11. Comparison of average throughput of different schemes with increasing SINR value

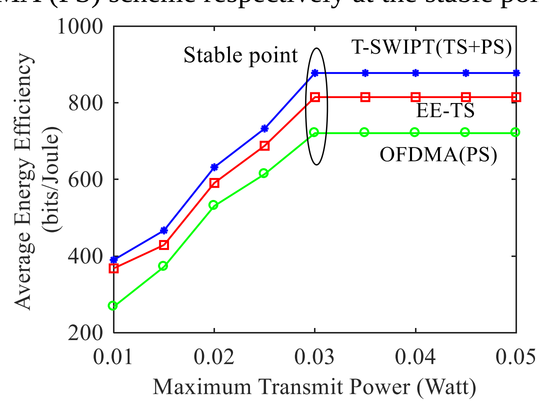

Fig. 12. Comparison of average energy efficiency of different schemes with increasing maximum transmit power P_{max}

Fig. 12 shows that the proposed T-SWIPT techique outperforms with resepct to OFDMA (PS enabled) and EE-TS enabled schemes subject to energy efficiency for different maximum transmit power. The reason for perfroming better (T-SWIPT) than other schemes is mentioned in the above comparison of system throughput. Further, EE-TS scheme's average energy efficeincy is better than OFDMA (PS) scheme. When the received signal is already weak (maximum transmit power region of transmiter node $P_{max} < 0.02$ W), and there is again signal division in OFDMA (PS), it causes inadequacy in information decoding and energy harvesting. Because, most of the power in splitted signal is consumed only in triggering the EH circuit or ID circuit, and very low amount of power is left for energy harvesting and information decoding. Thus, reduces the energy efficiency of the system. Whereas, in EE-TS enabled protocol for low power received signal, system want to increase the

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transmit power by providing more time to energy harvesting circuit and less time to information decoding so ultimately average energy efiicency decreases. It is observed that, energy efficiency of all the three system increases with increase in the value of transmit power till the obtained energy efficiency acquires its optimal value for the high intensity of transmission power and become stable for maximum allowance transmit power greater than $0.03W$. However, energy efficiency of the proposed T-SWIPT technique turns out to be better as compared to the existing systems. Because in T-SWIPT advantages of both PS and TS protocols are considered which allows the network to harvest more energy and decode more number of data bits successfully, thus overcome the disadvantages of using only PS or TS protocol. Overall, T-SWIPT improves average energy efficiency by 11% and 21 % over EE-TS and OFDMA (PS) scheme respectively at stable point.

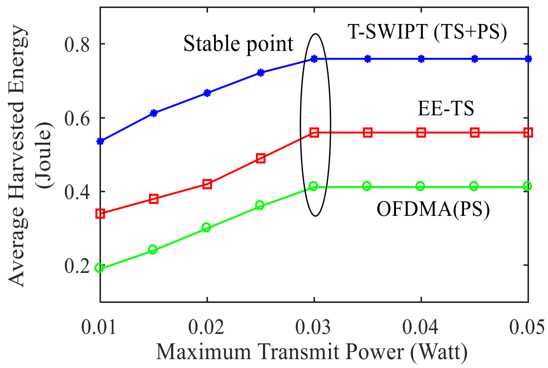

Fig.13. Comparison of average harvested energy with increasing maximum transmit power P_{max}

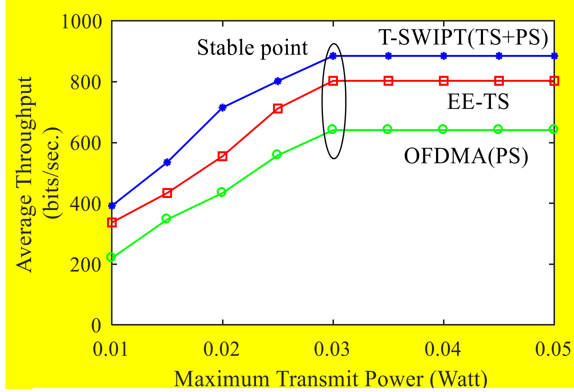

Fig.14. Comparison of average throughput of different schemes with increasing maximum transmit power P_{max}

Fig. 13 illustrates that the average harvested energy of all the three systems increases with the increment of allocated maximum transmit power utill average harvested energy reaches its optimum value and become stable for $P_{max} > 0.03\ W$. However, it can be seen that the proposed T-SWIPT technique harvests more energy as compared to the existing systems. Because in the proposed T-SWIPT technique both PS and TS protocols for energy harvesting are integrated. Sensor nodes harvest energy from its intended received signals, sink or other unintended neighboring transmitting node in a time switching manner. Whereas, Fig. 14 illustrates the comparative analysis of the average throughput of state-of-the-art-schemes over increasing region of maximum allowed transmit power corresponds to the Fig .13. It can be clearly observed that average throughput follow almost the same growth rate as the average harvested energy increases over maximum transmit power and becomes stationary at 0.03W. This is because, higher harvested energy empowers the transmitter to increase its RF transmission signal strength close to the allowed region P_{max}, and more number of data bits are successfully transmitted in unit time.

While in OFDMA (PS) and EE-TS energy harvesting is done only through intended received signals energy. Further, PS protocol has disadvantage when the received signal is too weak. If the received weak signal power is divided for energy harvesting, it causes inadequacy in energy harvesting in PS protocol based SWIPT (OFDMA). Because most of the power is consumed in conversion circuit and very less amount of energy is output as DC power. Ultimately, low powered RF signal is transmitted and finally throughput of system reduces, as receiver is unable to successfully decode the information from received signal. Whereas, EE-TS enabled protocol in the case of low power received signal does not has enough power to trigger the energy harvesting circuit and fails to provide minimum output power for next hop transmission. In addition to these, dynamic adaptability of transmission power in the TS or PS schemes is also absent. Thus, the harvested energy and throughput is less in both the system as compared to the proposed T-SWIPT scheme. Further, overall T-SWIPT harvests more energy than EE-TS and OFDMA (PS) schemes by 43% and 92 % respectively, and corresponding gain in the throughput for the T-SWIPT scheme over EE-TS and OFDMA (PS) scheme are by 26 % and 48 % respectively at stable point.

5.2.4 Network-Wide Performance

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In this subsection, we evaluate the performance of system on increasing/decreasing the observation area or numbers of sensor nodes dispersed in the environment under maximum allowance transmit power $P_{max} = 0.03W$ subject to average energy efficiency.

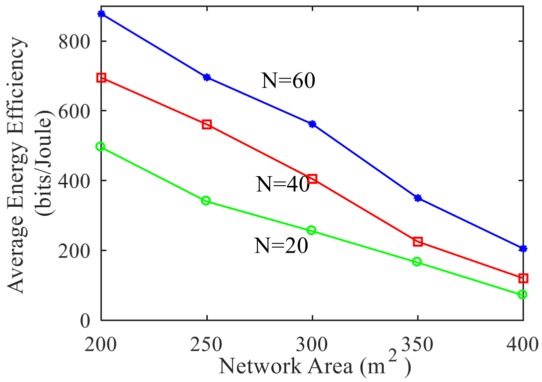

Fig.15. Average energy efficiency with increasing network area.

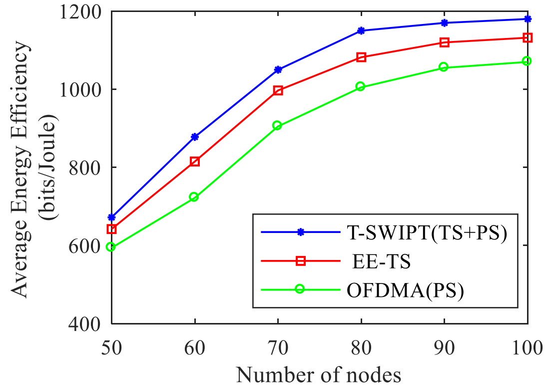

Fig.16. Comparison of Average energy efficiency with increasing number of sensor nodes.

Fig. 15 illustrates that on increasing the area of network with fixed number of sensors, the average energy efficiency of the network decreases quickly in T-SWIPT technique. It mainly depends upon two facts- (i) distance between the neighboring nodes increases and then harvested energy from them decreases; (ii) large distance among nodes causes more power consumption for data transmission and also effect of attenuation increases on signal, which further decreases the SINR level at receiver side (data rate decreases). It is also seen from the Fig.15 that with higher number of nodes in the fixed observation area leads to higher energy efficiency. This is because more number of nodes reduce the gap between neighboring nodes and energy harvesting from them increases, and also for data transmission relay-distance decreases as compared to the distribution of lower number of nodes in the area.

From the Fig. 16, it is observed that on increasing the number of nodes in the fixed area $100 \times 100\, m^2$ the average energy efficiency increases in all the schemes. The reason behind is- (i) uniform distribution helps the system to reduce inference level and appropriate selection of relay in data transmission; (ii) more number of nodes leads to sense and transmit more data to sink, which increases the data rate of the system; (iii) it also helps to cooperate in energy harvesting. However, on further increasing the number of nodes ($N > 80$) in the fixed area, network power consumption rises tremendously and it does not compensate the data rate loss and interference, and increasing rate of average energy efficiency slow down. We also analyzed that, the proposed T-SWIPT scheme outperforms the TS and PS driven scheme. Because, in T-SWIPT advantages of both PS and TS protocols are considered which allows the network to harvest more energy and decode more number of data bits successfully.

6. Conclusion and Future work

In this paper, we have proposed a novel T-SWIPT technique for a relay based energy harvesting IoT. The aim of the paper is to give the optimum strategies for transmit power allotment; decide the optimum power splitting ratio and the optimum energy broadcast slot for the sink. In order to attain this aim, the problem of energy efficiency optimization is formulated as a non-convex maximization problem. Lagrangian based optimization algorithm is used to convert the problem into convex maximization problem in order to obtain the optimal solution. The outcomes of the simulation prove that the convergence of algorithm-1 takes place in a few numbers of iterations. In addition, the simulation results of the proposed technique are better than the state-of-the-art schemes in terms of energy efficiency, system throughput and energy harvesting. However, SWIPT technique has some technical issues that must be addressed such as poor energy transfer efficiency, scheduling, security in data transmission, etc. In the future research work, we will plan to consider the above issues of SWIPT technique and provide the optimal solution for it. In addition, we will use the concept of virtual multiple-input multiple-output with security aspects of SWIPT technique and try to give optimal solution for providing physical layer security.

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Appendix-A

Proof of Quasi-concavity of the maximization problem with respect to optimization variables

The energy efficiency objective function from Eq. (11) is given as follow:

$$max_{P,\tau,\beta}\ \psi\ (P,\tau,\beta) = \frac{\omega(P,\tau,\beta)}{E_{TC}(P,\tau,\beta)}$$

It is observed that the maximization problem is a fraction of concave (numerator) to convex (denominator) function. In the next three cases, we proved that numerator $\omega(P,\tau,\beta)$ is concave function.

(A.1) Proof of Numerator $\omega(P,\tau,\beta)$ as concave function

Case-1: The first and second order partial derivative of $\omega(P,\tau,\beta)$ with respect to transmit power P_{ij}, for the given τ_{ij} *and* β are computed as follow :

$$\frac{\partial\omega}{\partial P_{ij}} = (\tau_{ij}Vg_{ij}t\delta_{ij})/(log(2)(\sigma^2_{S,i,j} + \tau_{ij}(\sigma^2_{I,i,j} + \sigma^2_{A,i,j}))((\tau_{ij}P_{ij}g_{ij})/(\sigma^2_{S,i,j} + \tau_{ij}(\sigma^2_{I,i,j} + \sigma^2_{A,i,j})) + 1)) \quad \text{(A-1)}$$

$$\frac{\partial^2\omega}{(\partial P_{ij})^2} = -\left(\tau_{ij}{}^2Vg_{ij}{}^2t\delta_{ij}\right)/\left(log(2)\left(\sigma^2_{S,i,j} + \tau_{ij}\left(\sigma^2_{I,i,j} + \sigma^2_{A,i,j}\right)\right)^2\left(\frac{\tau_{ij}P_{ij}g_{ij}}{\sigma^2_{S,i,j} + \tau_{ij}\left(\sigma^2_{I,i,j}+\sigma^2_{A,i,j}\right)} + 1\right)^2\right) \quad \text{(A-2)}$$

Here, $\frac{\partial^2\omega}{(\partial P_{ij})^2} < 0$

Case-2: The first and second order partial derivative of $\omega(P,\tau,\beta)$ with respect to power splitting ratio τ_{ij} for the given P_{ij} and β are computed as follow :

$$\frac{\partial\omega}{\partial\tau_{ij}} = (Vt\delta_{ij}((P_{ij}g_{ij})/(\sigma^2_{S,i,j} + \tau_{ij}(\sigma^2_{I,i,j} + \sigma^2_{A,i,j})) - (\tau_{ij}P_{ij}g_{ij}(\sigma^2_{I,i,j} + \sigma^2_{A,i,j}))/(\sigma^2_{S,i,j} + \tau_{ij}\left(\sigma^2_{I,i,j} + \sigma^2_{A,i,j}\right))^2))/(log(2)((\tau_{ij}P_{ij}g_{ij})/(\sigma^2_{S,i,j} + \tau_{ij}(\sigma^2_{I,i,j} + \sigma^2_{A,i,j})) + 1)) \quad \text{(A-3)}$$

$$\frac{\partial^2\omega}{(\partial\tau_{ij})^2} = -\ (Vt\delta_{ij}((P_{ij}g_{ij})/(\sigma^2_{S,i,j} + \tau_{ij}(\sigma^2_{I,i,j} + \sigma^2_{A,i,j})) - (\tau_{ij}P_{ij}g_{ij}(\sigma^2_{I,i,j} + \sigma^2_{A,i,j}))/(\sigma^2_{S,i,j} + \tau_{ij}\left(\sigma^2_{I,i,j} + \sigma^2_{A,i,j}\right))^4)/(log(2)((\tau_{ij}P_{ij}g_{ij}(\sigma^2_{S,i,j} + \tau_{ij}(\sigma^2_{I,i,j} + \sigma^2_{A,i,j})) + 1)^2) - (Vt\delta_{ij}((2P_{ij}g_{ij}(\sigma^2_{I,i,j} + \sigma^2_{A,i,j}))/(\sigma^2_{S,i,j} + \tau_{ij}\left(\sigma^2_{I,i,j} + \sigma^2_{A,i,j}\right))^2 - (2\tau_{ij}P_{ij}g_{ij}\left(\sigma^2_{I,i,j} + \sigma^2_{A,i,j}\right)^2)/((\sigma^2_{S,i,j} + \tau_{ij}\left(\sigma^2_{I,i,j} + \sigma^2_{A,i,j}\right))^3))/(log(2)((\tau_{ij}P_{ij}g_{ij})/(\sigma^2_{S,i,j} + \tau_{ij}(\sigma^2_{I,i,j} + \sigma^2_{A,i,j})) + 1)) \quad \text{(A-4)}$$

Here, $\frac{\partial^2\omega}{(\partial\tau_{ij})^2} < 0$

Case-3: The first and second order partial derivative of the $\omega(P,\tau,\beta)$ with respect to energy broadcast time slot β for sink for the given P_{ij} and τ_{ij} is computed as follow:

$$\frac{\partial\omega}{\partial\beta} = -\ (V\delta_{ij}log((\tau_{ij}P_{ij}g_{ij})/(\ \sigma^2_{S,i,j} + \tau_{ij}\left(\sigma^2_{I,i,j} + \sigma^2_{A,i,j}\right)) + 1))/(c*log(2) \quad \text{(A-5)}$$

Here, $\frac{\partial^2\omega}{(\partial\beta)^2} = 0$

Overall, we observe that the second order partial derivative of $\omega(P,\tau,\beta)$ is non-increasing function with respect to optimization variables (negative value), thus it is proved that the total data rate of network $\omega(P,\tau,\beta)$ is concave function under optimization variables.

(A.2) Proof of denominator $E_{TC}(P,\tau,\beta)$ as an affine function, proved as positive convex function.

An affine function is a function which is composed of a linear function + a constant.

Case-1: $E_{TC}(P,\tau,\beta)$ is an affine function (convex) with respect to P_{ij}

Proof:

$$E_{TC}\left(P_{ij},\tau_{ij},\beta\right) = P_cT + \mu P_{ij}t - E^j_{TH} \quad \text{(A-6)}$$

$$E_{TC} = P_cT + \mu P_{ij}t - \sum_{i=1}^{d} P_{ij}\varepsilon_j(1-\tau_{ij})\eta_{ij}g_{ij}t - \sum_{i=1}^{d}\left(\sigma^2_{I,ij} + \sigma^2_{A,ij}\right)\eta_{ij}(1-\tau_{ij})t - P_s\varepsilon_j\eta_{ij}g_{ij}\beta - \sum_{i=1}^{m} P_{ij}\varepsilon_j\eta_{ij}g_{ij}\,t(1-a_{ij}) \quad \text{(A-7)}$$

Affine function form:

$$E_{TC} = P_{ij}\left(\mu t - \sum_{i=1}^{d} \varepsilon_j (1-\tau_{ij}) \eta_{ij} g_{ij} t - \sum_{i=1}^{m} P_{ij}\varepsilon_j \eta_{ij} g_{ij}\, t(1-a_{ij})\right) + \left(P_c T - \sum_{i=1}^{d}\left(\sigma_{I,i,j}^2 + \sigma_{A,i,j}^2\right)\eta_{ij}(1-\tau_{ij})t - P_s \varepsilon_j \eta_{ij} g_{ij}\beta\right) \quad \text{(A-8)}$$

E_{TC} is of the form $aP_{ij}+b$ with a and b constant. Thus, it is an affine function. Where,

$$a = \left(\mu t - \sum_{i=1}^{d} \varepsilon_j (1-\tau_{ij}) \eta_{ij} g_{ij} t - \sum_{i=1}^{m} P_{ij}\varepsilon_j \eta_{ij} g_{ij}\, t(1-a_{ij})\right)$$

$$b = \left(P_c T - \sum_{i=1}^{d}\left(\sigma_{I,i,j}^2 + \sigma_{A,i,j}^2\right)\eta_{ij}(1-\tau_{ij})t - P_s \varepsilon_j \eta_{ij} g_{ij}\beta\right)$$

Case-2: $E_{TC}(P,\tau,\beta)$ is an affine function (convex) with respect to τ_{ij}

Proof:

$$E_{TC} = P_c T + \mu P_{ij} t - \sum_{i=1}^{d} P_{ij}\varepsilon_j (1-\tau_{ij}) \eta_{ij} g_{ij} t - \sum_{i=1}^{d}\left(\sigma_{I,ij}^2 + \sigma_{A,ij}^2\right)\eta_{ij}(1-\tau_{ij})t - P_s \varepsilon_j \eta_{ij} g_{ij}\beta - \sum_{i=1}^{m} P_{ij}\varepsilon_j \eta_{ij} g_{ij}\, t(1-a_{ij}) \quad \text{(A-9)}$$

Affine function form:

$$E_{TC} = \tau_{ij}\left(\sum_{i=1}^{d} P_{ij}\varepsilon_j \eta_{ij} g_{ij} t + \sum_{i=1}^{d}\left(\sigma_{I,i,j}^2 + \sigma_{A,i,j}^2\right)\eta_{ij} t\right) + \left(P_c T + \mu P_{ij} t - P_s \varepsilon_j \eta_{ij} g_{ij}\beta - \sum_{i=1}^{m} P_{ij}\varepsilon_j \eta_{ij} g_{ij}\, t(1-a_{ij}) - \sum_{i=1}^{d} P_{ij}\varepsilon_j \eta_{ij} g_{ij} t - \sum_{i=1}^{d}\left(\sigma_{I,i,j}^2 + \sigma_{A,i,j}^2\right)\eta_{ij} t\right) \quad \text{(A-10)}$$

E_{TC} is of the form $a\tau_{ij} + b$ with a and b constant. Thus, it is an affine function. Where,

$$a = \left(\sum_{i=1}^{d} P_{ij}\varepsilon_j \eta_{ij} g_{ij} t + \sum_{i=1}^{d}\left(\sigma_{I,i,j}^2 + \sigma_{A,i,j}^2\right)\eta_{ij} t\right)$$

$$b = \left(P_c T + \mu P_{ij} t - P_s \varepsilon_j \eta_{ij} g_{ij}\beta - \sum_{i=1}^{m} P_{ij}\varepsilon_j \eta_{ij} g_{ij}\, t(1-a_{ij}) - \sum_{i=1}^{d} P_{ij}\varepsilon_j \eta_{ij} g_{ij} t - \sum_{i=1}^{d}\left(\sigma_{I,i,j}^2 + \sigma_{A,i,j}^2\right)\eta_{ij} t\right)$$

Case-3: $E_{TC}(P,\tau,\beta)$ is an affine function (convex) with respect to β

Proof:

$$E_{TC} = P_c T + \mu P_{ij}\left(\frac{T-\beta}{c}\right) - \sum_{i=1}^{d} P_{ij}\varepsilon_j (1-\tau_{ij}) \eta_{ij} g_{ij}\left(\frac{T-\beta}{c}\right) - \sum_{i=1}^{d}\left(\sigma_{I,ij}^2 + \sigma_{A,ij}^2\right)\eta_{ij}(1-\tau_{ij})\left(\frac{T-\beta}{c}\right) - P_s \varepsilon_j \eta_{ij} g_{ij}\beta - \sum_{i=1}^{m} P_{ij}\varepsilon_j \eta_{ij} g_{ij}\left(\frac{T-\beta}{c}\right)(1-a_{ij}) \quad \text{(A-11)}$$

Affine function form:

$$E_{TC} = \beta\left(\left(\frac{\sum_{i=1}^{d} P_{ij}\varepsilon_j (1-\tau_{ij}) \eta_{ij} g_{ij}}{c}\right) + \frac{\sum_{i=1}^{d}\left(\sigma_{I,ij}^2 + \sigma_{A,ij}^2\right)\eta_{ij}(1-\tau_{ij})}{c} - -P_s \varepsilon_j \eta_{ij} g_{ij} - \left(\frac{\mu P_{ij}}{c}\right) + \frac{\sum_{i=1}^{m} P_{ij}\varepsilon_j \eta_{ij} g_{ij}(1-a_{ij})}{c}\right) + \left(P_c T + \frac{\mu P_{ij} T}{c} - \left(\frac{\sum_{i=1}^{d} P_{ij}\varepsilon_j (1-\tau_{ij}) \eta_{ij} g_{ij} T}{c}\right) - \frac{\sum_{i=1}^{d}\left(\sigma_{I,ij}^2 + \sigma_{A,ij}^2\right)\eta_{ij}(1-\tau_{ij})T}{c} - \frac{\sum_{i=1}^{m} P_{ij}\varepsilon_j \eta_{ij} g_{ij}(1-a_{ij})T}{c}\right) \quad \text{(A-12)}$$

E_{TC} is of the form $a\beta + b$ with a and b constant. Thus, it is an affine function. Where,

$$a = \left(\left(\frac{\sum_{i=1}^{d} P_{ij}\varepsilon_j (1-\tau_{ij}) \eta_{ij} g_{ij}}{c}\right) + \frac{\sum_{i=1}^{d}\left(\sigma_{I,ij}^2 + \sigma_{A,ij}^2\right)\eta_{ij}(1-\tau_{ij})}{c} - P_s \varepsilon_j \eta_{ij} g_{ij} - \left(\frac{\mu P_{ij}}{c}\right) + \frac{\sum_{i=1}^{m} P_{ij}\varepsilon_j \eta_{ij} g_{ij}(1-a_{ij})}{c}\right)$$

$$b = \left(P_c T + \frac{\mu P_{ij} T}{c} - \left(\frac{\sum_{i=1}^{d} P_{ij}\varepsilon_j (1-\tau_{ij}) \eta_{ij} g_{ij} T}{c}\right) - \frac{\sum_{i=1}^{d}\left(\sigma_{I,ij}^2 + \sigma_{A,ij}^2\right)\eta_{ij}(1-\tau_{ij})T}{c} - \frac{\sum_{i=1}^{m} P_{ij}\varepsilon_j \eta_{ij} g_{ij}(1-a_{ij})T}{c}\right)$$

Therefore, the energy efficiency objective function $\psi\,(P,\tau,\beta)$ is the ratio of a concave function to an affine function and results in a quasi-concave function.