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RESEARCH ARTICLE

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# Joint time-slot and power allocation algorithm for data and energy integrated networks supporting internet of things (IoT)

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**Summary**

IoT is an essential enabler for smart cities and smart society. However, its deployment at large scale faces a big challenge: battery replacement as most IoT devices are battery-powered or even battery-less. In a hostile environment, it is infeasible to replace batteries. Radio frequency (RF)-enable wireless energy transfer (WET) is a promising technology to solve this problem. Since RF is also used for wireless data communication, a data and energy integrated network (DEIN) is the way forward. Based on the DEIN technology, a time allocation model is designed in this paper to manage the RF energy and uplink data transmission in different time slots. In the IoT scenario, the DEIN's primary service is to collect environmental information such as temperature, humidity, and luminance. Therefore, the uplink data transmission of the battery-powered/battery-less IoT nodes deserves more attention. To increase the uplink data transmission in case of consuming less energy in the DEIN system, we propose a joint time slot and power allocation algorithm to minimize the system's consumed energy for transmitting per bit of uplink data. It aims to maximize the efficiency of the DEIN system's energy utilization, which helps to achieve an energy-efficient DEIN.

**KEYWORDS**

data and energy integrated networks (DEIN), IoT, resource allocation, RF charging, wireless energy transfer (WET)

## 1 | INTRODUCTION

According to the forecast, there will be around 41.6 billion IoT devices connected to the network by 2025.[1] The rapidly increased IoT devices bring enormous pressure to the energy management work as most of them are battery-powered gadgets. What's more, some commercially used IoT wireless sensors are deployed in the extreme environment such as on the roof, underneath the floor, and embeds in the wall. It brings more challenges to battery replacement works. To release the pressure on manual works for energy management, some approaches have been made to use RF energy transmission/harvesting technology to supply the IoT devices[2-5] Furthermore, by merging this technology into the existing network system, a novel network, namely, the Data and Energy Integrated Network (DEIN) is proposed,[6,7] which is also widely known as simultaneous wireless information and power transfer (SWIPT) system.[8] The enabling technologies for related hardware realization are RF charging/harvesting, wireless power transfer, SWIPT receiver architecture, and so forth.[9] The applicable scenarios for SWIPT system are wireless sensor networks (WSN), relay networks, collaborative mobile clouds, cognitive radio networks, and so forth.[10,11]

In the DEIN system, due to the massive RF energy attenuation in the air and the energy loss during RF-to-DC conversion, the RF energy transmission technology is uneconomic in energy transmission from the RF transmitter to the receiver. According to literature, most of the research focus on minimizing the SWIPT transmitter's transmission power to reduce the energy consumption to improve system energy efficiency. Some of them consider the multiple-input single-output (MISO) broadcast system for SWIPT and optimally design the robust beamforming and power splitting to minimize the transmission power.[12-14] Some of them study the optimization problem for minimizing the transmission power[15,16] or maximizing the energy efficiency[17] in SWIPT system involved in the non-orthogonal multiple access (NOMA) based networks. The motivation of this paper is to increase the efficiency of energy utilization to achieve an energy-efficient DEIN. In other words, we want to minimize the system's consumed energy for transmitting per bit of uplink data. According to our specific IoT scenario, the RF energy receivers are also wireless network devices for gathering and reporting environmental information. Hence, the uplink data transmission from the receivers is the major system service. The receivers are designed as the battery-less mode and rely on receiving the RF energy from the RF energy transmitter. Hence, the system's consumed energy is the total energy consumption in the RF energy transmitter. Since the system's service depends on the uplink data from all involved RF energy receivers, we aim to supply more uplink data when the same energy is consumed in the system. As a result, we have made the following contributions in this work:

- We propose a DEIN architecture involving a single transmitter and multiple receivers.
- We propose a joint time slot and power allocation algorithm to minimize the DEIN system's energy consumption per bit of uplink data.
- We give a specific hardware circuit design scheme of DEIN transmitter and receiver.

## 2 | RELATED WORKS

According to literature, most of the SWIPT systems are implemented based on the power splitter (PS)[18-20] or time switching (TS)[21-23] mode receiver architecture. The transmitter is designed to deliver both wireless energy and information to the receiver. PS mode receiver split the received signal for independent energy and information receptions. The PS ratio defines the energy ratio for energy harvesting (EH) or information decoding (ID). By contrast, the TS mode receiver utilizes different time duration to receive wireless energy or information. According to different receiving architectures, many research focuses on minimizing the transmitter's transmission power to improve system efficiency.

Mao et al.[24] minimize the system total power consumption in a distributed MISO downlink SWIPT system. A part of user equipment (UEs) are deployed with EH function, and the rest UEs only have the ID function. In their SWIPT system, the remote antenna units (RAUs) are geographically separated, which structures a distributed antenna system. The RAUs transfer RF energy and wireless information to their nearby EH UEs. The EH UEs are designed as PS mode with a single antenna. Based on the distributed MISO system, Mao et al.[24] formulate the optimization problem to minimize the system total power consumption which is subject to the constraints of the minimum required signal-to-interference-plus-noise ratio (SINR) for all UEs and the energy charging threshold for all the EH UEs. It aims to solve the optimization problem by working out the optimal PS ratio for all the EH UEs and the beamforming vector of all UEs. Cai et al.[25] study the joint transceiver design problem for their proposed multiuser MISO relay SWIPT system. It consists of a base station (BS), a relay station (RS) and multiple UEs. All the UEs are designed with EH function and PS mode. Cai et al.[25] aim to minimize the total transmission power of both BS and RS, which is subject to UEs' SINR and EH constrains. Their proposed optimization problem aims to work out the BS beamforming vectors, the RS amplify-and-forward transformation matrix, and the PS ratio for each UE. Furthermore, Xu et al.[26] study the total transmit power minimization problem for their proposed multi-relay assisted SWIPT system. The system consists of a macro BS, multiply relays and EH users. All the EH users are designed with PS mode, which receives RF energy from their nearby relays. The optimization problem is proposed to minimize the sum of the transmission power from all the relays to the EH users. It constrained by the target rates at relays and EH users as well as the energy threshold at EH users.

Hu et al.[27] studies a mobile edge computing (MEC) system in which two mobile devices are energized by the wireless power transfer (WPT) from an access point (AP) and they can offload part or all of their computation-intensive latency-critical tasks to the AP connected with an MEC server or an edge cloud. They aim to minimize the AP's total transmit energy subject to the constraints of the computational tasks.

In contrast to the approaches of power minimization for the PS mode based SWIPT system, the power optimization problem is also studied in the TS mode based SWIPT system. Lee et al.[28] study a scheme to jointly allocate time durations for the ID and EH for each TS mode based SWIPT receiver. According to the scheme, they formulate an optimization problem to minimize the average transmit power under the constraint of each receiver's information rate. They aim to find the optimal TS ratio for each receiver and the transmit covariance matrices for the unique transmitter. By contrast, Jiang et al.[29] study the transmit power minimization problem on a PS and TS coexisting SWIPT system. They solve the optimization problem by jointly optimizing the transmit beamforming vector of the unique SWIPT transmitter, the PS and TS ratios of the receivers under the constraints of the user's information rate and the harvested energy.

Unlike other works that only consider power allocation or time allocation to improve the energy efficiency, we consider both at the same time. Also, an algorithm has been proposed to minimize the consumed energy per bit of uplink data based on a DEIN topology involving a single transmitter and multiple receivers. The remainder of this chapter is organized as follows. Section 3 describes the structure of the transmitter and receiver in the proposed DEIN system as well as the system topology. Section 4 describes the proposed system models such as the energy estimation model and joint time slot allocation model. Besides, the problem of how to minimize the system's energy consumption per bit of uplink data is proposed. Section 5 describes the method and related algorithm to solve the proposed problem. Section 6 evaluates the performance of the algorithm, and the numeric results prove its validity. Section 7 is the conclusion.

## 3 | DATA AND ENERGY INTEGRATED NETWORK

### 3.1 | Transmitter and receiver

Our proposed DEIN is implemented by applying the hard modification to a typical ZigBee based WSN.[30] The ZigBee router is designed as the Data and Energy Integrated Network Transmitter (DEINT) and the ZigBee end device is designed as the Data and Energy Integrated Network Receiver (DEINR). Figure 1 shows the block structure of the DEINT and DEINR. The DEINT is structured with the DC supplier, ZigBee module, RF path selector, RF power amplifier and two antennas. The ZigBee module is configured as a ZigBee router by software. The RF path selector is a single-pole, double-throw switch. The single input pin of the RF path selector is connected to the unique RF interface of the ZigBee module. Hence, the GPIO port of the ZigBee module controls the switch for transmission and receiving mode. The RF power amplifier is used for increasing the transmission power, and the enhanced waves are treated as the RF energy to the DEINR.

The DEINR is designed as a battery-less mode. The ZigBee module on the DEINR is configured as a ZigBee end device, and its Omni antenna is used for uplink and download data transmission. The directional antenna is used for receiving RF energy. The impedance match circuitry maximizes the received RF energy from the antenna. The rectifier converts the RF waveform to DC voltage. The power management circuitry is used for harvesting the DC energy and

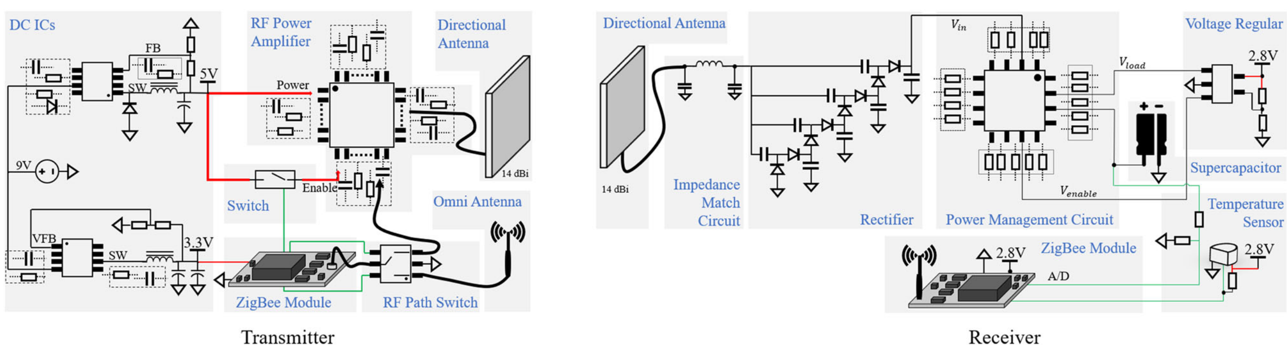


**FIGURE 1** The hardware structure of the DEIN's transmitter and receiver

store it to a super-capacitor. The voltage regulator regulates the super-capacitor's voltage to supply the ZigBee module and the sensor.

## 3.2 | System topology

Figure 2 describes the DEIN system involving a single DEINT and two DEINRs. The directional antenna of the DEINT is rotated to face the two DEINRs in different time slots for RF energy transmission. The RF energy transmission procedure is launched by the DEINT, which sends a series of customized packets with enhanced power. We name the customized packet as energy packet (EP). During time slot 1, the DEINT sends EPs to charge DEINR A. In time slot 2, the DEINT suspends the RF energy transmission and starts to turn its directional antenna anticlockwise. Meanwhile, DEINR A commences the uplink data transmission, and the uplink data is transmitted to the ZigBee router (DEINT). In time slot 3, the DEINT forwards the just-received uplink data to the ZigBee coordinator. Thereafter, in time slot 4, the DEINT's antenna is turned opposite to DEINR B and commences the RF energy transmission. Figure 3 describes the joint time slots allocation mechanism to manage the EPs and the uplink data transmission.

During the time slots for the RF energy transmission, the DEINRs always keep silence when they are receiving RF energy. After receiving the EPs, the DEINR will utilize and run out the just-harvested energy for uplink data transmission. That is to say, the amount of uplink data depends on the amount of harvested energy during the previous time slot. Based on the router function of the DEINT, all the uplink data of the DEINRs will be initially transmitted to the DEINT and then immediately forwarded to the ZigBee coordinator through the DEINT's transmission antenna.

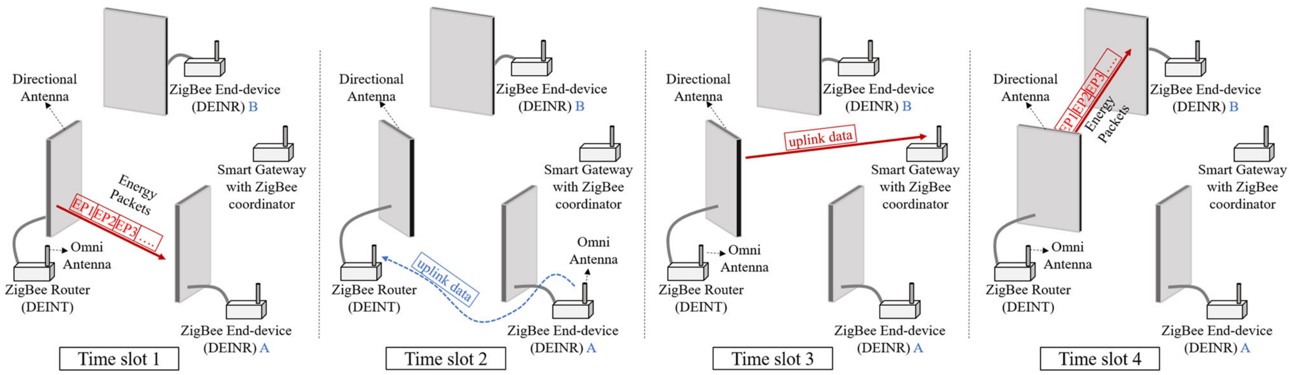


FIGURE 2 The DEIN system topology

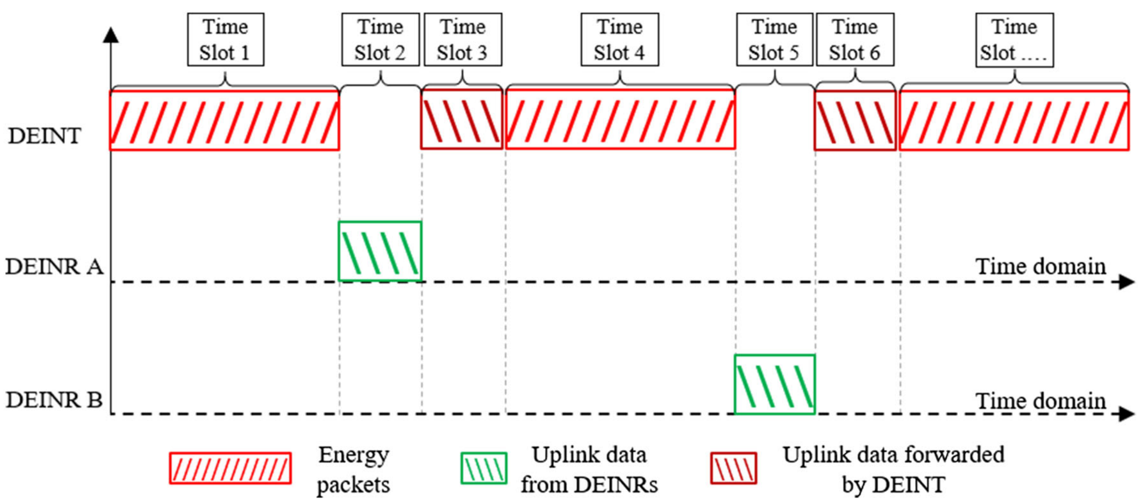


FIGURE 3 The allocated time slots for RF energy and uplink data transmission

# 4 | SYSTEM MODELING

## 4.1 | Energy estimation model

The block diagram depicted in Figure 4 models the consumed energy in both RF energy transmitter and receiver side. In addition, it models the progress of the RF-to-DC energy conversion for transmitting a *K*bit-length EP from the DEINT to the DEINR. All the related notations are listed in Table 1. The energy estimation model involves the estimated energy consumption for transmitting a *K* bit-length EP in the DEINT's RF power amplifier circuitry, the inductive energy from the DEINR's directional antenna by receiving the *K* bit-length EP, the estimated energy consumption in the receiver circuitry and the converted DC energy eventually stored in the super-capacitor.

By referring to the first-order radio model,[31] the energy consumption for transmitting a *K* bit-length EP in the DEINT's RF power amplifier is modeled as

$$E_T(K) = \varepsilon_{amp} \times K \times R^2 \tag{1}$$

where *K* is the number of bits contained in the EP. $\varepsilon_{amp}$ is the path loss character which indicates the energy attenuation speed of the transmitted EP. It has the unit of Joule per bit per square meter (J/bit/m$^2$). The *R* is the maximum dissipation distance of the RF energy waves, which is the longest distance the transmitted RF waves can reach.

It is assumed that the consumed energy in the RF power amplifier circuitry is totally converted to the energy contained in the transmitted RF waves. Hence, the $E_T(K)$ also represents the transmitted RF energy through transmitting a *K* bit-length EP, which equals the amount of the dissipated RF energy in the distance *R*. With the help of Friis transmission equation,[32] the relationship between the transmitted RF energy and the inductive energy from the DEINR's receiving antenna regarding the *K* bit-length EP is expressed as

$$\frac{E_I(K)}{E_T(K)} = \frac{P_r \times t}{P_t \times t} = G_r G_t \left(\frac{\lambda}{4\pi d}\right)^2 \tag{2}$$

where $E_I(K)$ is the inductive energy obtained from the DEINR's directional antenna. The $P_r$ and the $P_t$ are power fed into the transmission antenna and power delivered at the receiving antenna, respectively. The *t* is the duration of sending/receiving the *K* bit-length EP. The $G_r$ and $G_t$ are receiving and transmission antenna gains, respectively. The $\lambda$ is the wavelength of the radio frequency. The *d* is the practical RF energy transmission distance between the DEINT and the DEINR. After transforming Equation (2), the $E_I(K)$ is expressed as

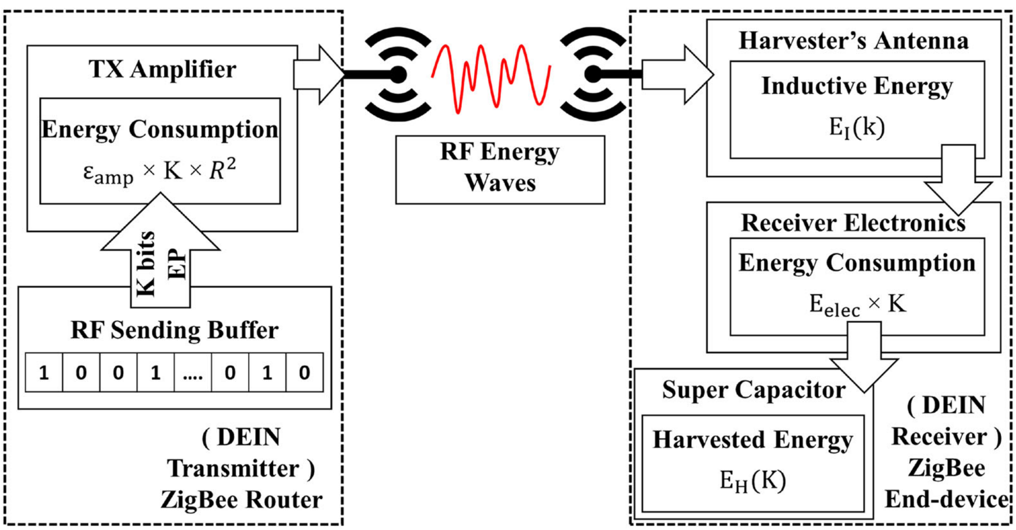


FIGURE 4 The energy estimation model[31] for transmitting a *K* bit-length EP from the DEINT to the DEINR

**TABLE 1** Involved notations in the system models

| Notation | Description |
|---|---|
| $t_{EP}$ | Allocated time for the DEINT to transmit EPs to a DEINR |
| $t_{DP}$ | Allocated time for a DEINR's uplink data transmission |
| $t_C$ | Sum of the $t_{EP}$ and the $t_{DP}$ |
| $R$ | Maximum dissipation distance of the RF energy waves |
| $\varepsilon_{amp}$ | Path loss character (joule per bit per square meter) |
| $B_{max}$ | Typical bandwidth of the ZigBee based network |
| $E_{elec}$ | Receiver circuitry's consumed energy by receiving single-bit EP |
| $G_r$ | Transmission antenna gain |
| $G_t$ | Receiving antenna gain |
| $\lambda$ | Wavelength of the RF energy waves |
| $d$ | Practical RF energy transmission distance |
| $P_{DEINT}$ | DEINT's transmission power |
| $P_{t_max}$ | Maximum transmission power of DEINT |
| $P_{TX}$ | DEINR's transmission power for transmitting uplink data |

$$E_I(K) = E_T(K) \times G_r G_t \left(\frac{\lambda}{4\pi d}\right)^2 \tag{3}$$

With the help of Equations (1) and (3), the harvested DC energy obtained by receiving a $K$ bit-length EP is expressed as the following equation by subtracting the estimated energy consumption in the receiving circuitry.

$$\begin{aligned} E_H(K) &= E_I(K) - E_{elec} \times K \\ &= E_T(K) \times G_r G_t \left(\tfrac{\lambda}{4\pi d}\right)^2 - E_{elec} \times K \\ &= \varepsilon_{amp} \times K \times R^2 \times G_r G_t \left(\tfrac{\lambda}{4\pi d}\right)^2 - E_{elec} \times K \end{aligned} \tag{4}$$

where $E_H(K)$ represents harvested DC energy stored in the super-capacitor by receiving a $K$ bit-length EP. The $E_{elec}$ is the estimated energy consumption by receiving a single bit of an EP in the receiving circuitry. The $E_H(K)$ must be greater then 0. It means there is DC energy harvested by the DEINR to supply their uplink data transmission. Hence, the following constraint should be met in the energy estimation model.

$$C1 : E_H(K) > 0 \tag{5}$$

## 4.2 | The time allocation model

As the DEINR's uplink data transmission relies on the harvested RF energy in the previous time slot, the time is allocated separately for receiving RF energy (the EPs) and transmitting uplink data (ZigBee DPs) for the DEINR. The time allocation model is described in Figure 5, which models the time period from the beginning of the RF energy charging/harvesting process to the finishing time point of the successful uplink data transmission process. The time $t_{EP}$ is

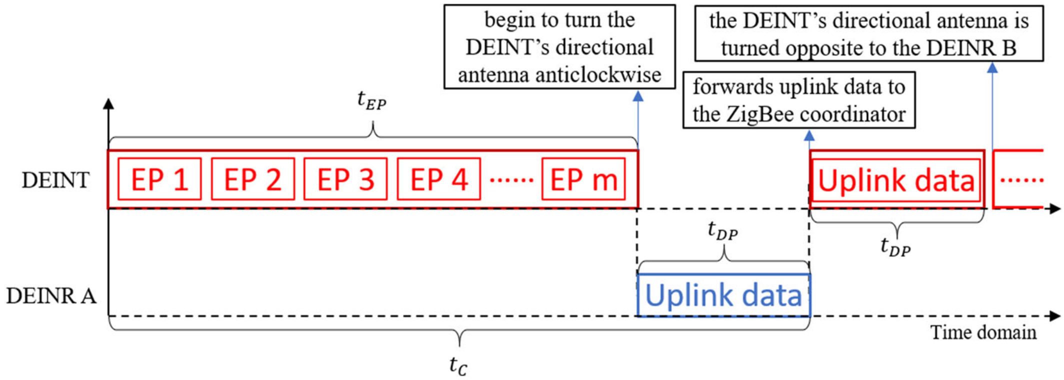


FIGURE 5 The joint time slot allocation model for managing EPs and uplink data

allocated for the DEINT to transmit a series of EPs to charge the DEINR A. At the end of the time $t_{EP}$, the DEINT's directional antenna begins to revolve anticlockwise towards to the ZigBee coordinator, and the DEINR A immediately triggers the process to transmit the uplink data to the DEINT, namely, the ZigBee router. We use the same RF chip on the DEINT and DEINR, with the same data transmission rate, which is up to 250 kbps. Since the DEINT only forwards the data packets of the DEINR, the amount of data sent by DEINT and DEINR is the same. So the time consumed is also the same, we call it $t_{DP}$. The length of the $t_{DP}$ depends on how much energy is harvested in time $t_{EP}$. The time $t_C$ is the sum of the $t_{EP}$ and $t_{DP}$. According to the time allocation model, the maximum number of bits involved in the uplink data transmission during the time $t_{DP}$ is modeled as

$$\begin{aligned} D_{uplink} &= t_{DP} \times B_{max} \\ &= (t_C - t_{EP}) \times B_{max} \\ &= B_{max} \times t_C - K \times m, \forall m \in \mathbb{N} \end{aligned} \tag{6}$$

where $B_{max}$ is the typical ZigBee bandwidth with the unit of bits per seconds, which indicates the maximum data transmission speed of the ZigBee based network. It is usually a pre-test value marked by the device manufacturer and recognized as a constant value in the DEIN system. The $K \times m$ is the overall number of bits involved in the EP stream throughout the time $t_{EP}$. Hence, the $D_{uplink}$ is the maximum number of bits of the uplink data can be generated and transmitted in the time $t_{DP}$, which relies on the harvested DC energy in the time $t_{EP}$.

As the harvested DC energy during the time $t_{EP}$ is exhausted by the DEINR A in the time $t_{DP}$, the following constraint must be met according to the time slot allocation model.

$$C2 : E_{uplink} = m \times E_H(K), \forall m \in \mathbb{N} \tag{7}$$

where

$$\begin{aligned} E_{uplink} &= P_{TX} \times t_{DP} \\ &= P_{TX} \times (t_C - t_{EP}) \\ &= P_{TX} \times \left( t_C - \frac{K \times m}{B_{max}} \right) \end{aligned}$$

The $E_{uplink}$ represents the consumed energy in the DEINR A for uplink data transmission during the time $t_{DP}$. The $P_{TX}$ is the transmission power configured in the RF power amplifier circuitry of the DEINR A for transmitting the uplink data to the DEINT. The $m \times E_H(K)$ represents the harvested DC energy by receiving $m$ EPs which have the same bit-length of $K$. It is worth nothing that we do not consider uplink data rate/size constraint as we assume that this constraint is always satisfied. This is reasonable because RF-based wireless energy transfer (WET) is only suitable for small battery-powered or battery-less end devices which typically generate very little amount of data to be transmitted uplink (e.g., a temperature sensor). Since there is only small amount of data to be transmitted we always assume that this little amount of uplink data transmission can be satisfied.

According to the time allocation model, the DEINT's transmission power for transmitting EPs can be estimated by the calculation that is dividing the total transmitted RF energy by the duration of this transmission. Hence, with the help of Equation (1), the DEINT's transmission power, namely, the $P_{DEINT}$, is expressed as

$$\begin{aligned} P_{DEINT} &= \frac{E_T(K)\times m}{t_{EP}} \\ &= \frac{\varepsilon_{amp}\times K\times R^2\times m}{\frac{K\times m}{B_{max}}} \\ &= \varepsilon_{amp}\times R^2\times B_{max} \end{aligned} \tag{8}$$

where the $P_{DEINT}$ represents the RF transmission power with the unit of watts. The estimated $P_{DEINT}$ is treated as the guidance for configuring the practical RF transmission power in the DEINT's RF power amplifier circuitry. Hence, its value is limited by the maximum RF transmission power that the RF power amplifier can supply. Therefore, the following constraint must be met.

$$C3: P_{DEINT} \leq P_{t_max} \tag{9}$$

### 4.3 | Problem formulation

Since the DEINR is the battery-less device, the only energy resource to the DEINR is the DEINT. The total consumed energy in the DEINT can be recognized as the system's total consumed energy. From Figure 5, we can know that the DEINT has two periods of time to work, one is $t_{EP}$ for sending EPs, and the other is $t_{DP}$ for forwarding DPs from DEINR. We assume that the transmit power of the transmitter is always $P_{DEINT}$. Hence, minimizing the system's total energy consumption for uplink data transmission, is to minimize the total consumed energy in the DEINT within the time period that transmitting a maximum amount of uplink data from DEINR to the ZigBee coordinator. Therefore, according to the time allocation model, the optimization problem for minimizing the system's total energy consumption for uplink data transmission is formulated as

$$\begin{aligned} P1: \underset{t_{EP},t_{DP},P_{DEINT}}{\text{Minimize}} & \frac{P_{DEINT}\times t_C}{D_{uplink}} \\ \text{subject to}: & C1-C3 \end{aligned} \tag{10}$$

where the $P_{DEINT} \times t_C$ represents the total of consumed energy in the DEINT from the beginning of the RF energy transmission process to the finishing time point of the uplink data transmission process. The $D_{uplink}$ is the maximum number of bits involved in the uplink data can be finally transmitted to the ZigBee coordinator during this period. Hence, the problem P1 aims to minimize the system's total consumed energy per bit of uplink data. To solve this problem, the optimally allocated time slots $t_{EP}$, $t_{DP}$ and the optimal transmission power $P_{DEINT}$ of the DEINT's needs to be optimized. In this formulated problem, C1 describes that the value of the $E_H(K)$ must be greater than 0. C2 describes that the exhausted energy in the DEINR during the process of uplink data transmission is equivalent to the just-harvested DC energy. C3 is the restrictions of transmission power can be configured in the DEINT's RF power amplifier circuitry.

## 5 | JOINT TIME SLOT AND POWER ALLOCATION ALGORITHM

### 5.1 | Transformation

In order to solve the optimization problem, the expression (10) needs to be transformed and analyzed. By introducing a notation, namely, the *Ind*, to represent the expression (10), the (10) is transformed as

$$\begin{aligned} Ind &= \frac{P_{DEINT} \times t_C}{D_{uplink}} \\ &= \frac{\varepsilon_{amp} \times R^2 \times B_{max} \times t_C}{B_{max} \times t_C - K \times m}, \forall m \in \mathbb{N} \end{aligned} \tag{11}$$

By considering the constrain C2, the $t_C$ can be obtained from the Equation (7). In addition, with the help of the Equation (1), the $t_C$ is expressed as

$$\begin{aligned} t_C &= \frac{m \times E_H(K)}{P_{TX}} + \frac{m \times K}{B_{max}} \\ &= \frac{m \times \left(\varepsilon_{amp} \times K \times R^2 \times G_r G_t \left(\frac{\lambda}{4\pi d}\right)^2 - E_{elec} \times K\right)}{P_{TX}} + \frac{m \times K}{B_{max}}, \forall m \in \mathbb{N} \end{aligned} \tag{12}$$

Thereafter, by replacing the $t_C$ in Equation (11) with the expression (12), Equation (11) is transformed as

$$Ind = \frac{\varepsilon_{amp} \times R^2 \times B_{max}}{B_{max} - \cfrac{1}{\cfrac{\varepsilon_{amp} \times R^2 \times G_r G_t \left(\frac{\lambda}{4\pi d}\right)^2 - E_{elec}}{P_{TX}} + \cfrac{1}{B_{max}}}} \tag{13}$$

By observing Equation (13), if the RF energy transmission distance ($d$) is fixed, only the argument $R$ is variable. Hence, the problem P1 formulated in (10) can be transformed to the mathematical problem P2, which aims to find the optimal value of $R$ to minimize the *Ind*.

$$\begin{aligned} P2: \ & \underset{R}{\text{Minimize}} \ Ind(R) \\ & \text{subject to}: C1, C3 \end{aligned} \tag{14}$$

## 5.2 | Solving the problem

To solve the problem P2, it is required to find the minimum value of the $Ind(R)$ within the boundary of the argument $R$. Hence, we calculate the first-order derivative to the $Ind(R)$ with respect to the argument $R$. Thereafter, we will see if there is a specific value (the zero point) of the $R$ can make the first-order derivative of the $Ind(R)$ equal to 0. Firstly, by transforming Equation (13), the $Ind(R)$ is expressed as

$$Ind(R) = \varepsilon_{amp} \times R^2 + \frac{P_{TX} \times \varepsilon_{amp} \times R^2}{G_r G_t \left(\frac{\lambda}{4\pi d}\right)^2 \times B_{max} \times \varepsilon_{amp} \times R^2 - B_{max} \times E_{elec}} \tag{15}$$

If we let

$$U(R) = \varepsilon_{amp} \times R^2 \tag{16}$$

By replacing $\varepsilon_{amp} \times R^2$ with $U$, (15) is transformed as

$$Ind(U) = U + \frac{P_{TX} \times U}{G_r G_t \left(\frac{\lambda}{4\pi d}\right)^2 \times B_{max} \times U - B_{max} \times E_{elec}} \tag{17}$$

By calculating the first-order derivative to (16) and (17), we have

$$\begin{aligned}\frac{d(Ind)}{d(U)} &= 1+\frac{P_{TX}\times\left(G_rG_t\left(\frac{\lambda}{4\pi d}\right)^2\times B_{max}\times U-B_{max}\times E_{elec}\right)}{\left(G_rG_t\left(\frac{\lambda}{4\pi d}\right)^2\times B_{max}\times U-B_{max}\times E_{elec}\right)^2}-\frac{P_{TX}\times G_rG_t\left(\frac{\lambda}{4\pi d}\right)^2\times B_{max}\times U}{\left(G_rG_t\left(\frac{\lambda}{4\pi d}\right)^2\times B_{max}\times U-B_{max}\times E_{elec}\right)^2}\\ &= 1-\frac{P_{TX}\times B_{max}\times E_{elec}}{\left(G_rG_t\left(\frac{\lambda}{4\pi d}\right)^2\times B_{max}\times U-B_{max}\times E_{elec}\right)^2}\end{aligned} \tag{18}$$

and

$$\frac{d(U)}{d(R)}=2\times\varepsilon_{amp}\times R \tag{19}$$

According to

$$\frac{d(Ind)}{d(R)}=\frac{d(Ind)}{d(U)}\cdot\frac{d(U)}{d(R)} \tag{20}$$

The first-order derivative to the $Ind(R)$ with respect to the argument $R$ is obtained as

$$\frac{d(Ind)}{d(R)}=\left(1-\frac{P_{TX}\times B_{max}\times E_{elec}}{\left(G_rG_t\left(\frac{\lambda}{4\pi d}\right)^2\times B_{max}\times\varepsilon_{amp}\times R^2-B_{max}\times E_{elec}\right)^2}\right)\times(2\times\varepsilon_{amp}\times R) \tag{21}$$

In order to find the zero value point of the $Ind(R)$, we need to find the specific value of $R$ to let (21) equal to 0. To simplify the calculation procedures, we can find the specific value of $U$ to let (18) equal to 0, which therefore make (21) equal to 0 because that the (19) is always greater than 0. After calculating, the following two zero value points make the (18) equal to 0.

$$U=\frac{B_{max}\times E_{elec}+\sqrt{P_{TX}\times B_{max}\times E_{elec}}}{G_rG_t\left(\frac{\lambda}{4\pi d}\right)^2\times B_{max}} \tag{22}$$

or

$$U=\frac{B_{max}\times E_{elec}-\sqrt{P_{TX}\times B_{max}\times E_{elec}}}{G_rG_t\left(\frac{\lambda}{4\pi d}\right)^2\times B_{max}} \tag{23}$$

By consider the constraint C1 in (5), also with the help of Equation (4), the expression of (5) can be transformed as

$$\varepsilon_{amp}\times R^2>\frac{E_{elec}}{G_rG_t\left(\frac{\lambda}{4\pi d}\right)^2} \tag{24}$$

According to (16), $U$ equals to $\varepsilon_{amp}\times R^2$, only the zero value point (22) meets the above constraint. Therefore, the correct zero value point ($R$) to let (21) equal to 0 is

$$R=\sqrt{\frac{B_{max}\times E_{elec}+\sqrt{P_{TX}\times B_{max}\times E_{elec}}}{G_rG_t\left(\frac{\lambda}{4\pi d}\right)^2\times B_{max}\times\varepsilon_{amp}}} \tag{25}$$

To prove that the calculated zero value point $R$ in (25) makes the $Ind(R)$ in (15) reach to its minimum value, we calculate the second-order derivative to the $Ind(R)$ in (15) with respect to the $R$. The process of proof are described as follows. By transforming Equation (21) we have

$$\frac{d(Ind)}{d(R)}=2\times\varepsilon_{amp}\times R-\frac{2\times P_{TX}\times\varepsilon_{amp}\times E_{elec}}{A^2\times B_{max}\times\varepsilon_{amp}^2\times R^3+\frac{E_{elec}^2\times B_{max}}{R}-2\times E_{elec}\times B_{max}\times A\times\varepsilon_{amp}\times R} \tag{26}$$

where the constant value $A$ is,

$$A=G_rG_t\left(\frac{\lambda}{4\pi d}\right)^2 \tag{27}$$

Then, its second-order derivative is

$$\begin{aligned}\frac{d^2(Ind)}{d(R)^2}&=2\times\varepsilon_{amp}+\frac{2\times P_{TX}\times E_{elec}\times\varepsilon_{amp}\times(3\times A^2\times B_{max}\times\varepsilon_{amp}^2\times R^2-E_{elec}^2\times B_{max}\times R^{-2}-2\times E_{elec}\times B_{max}\times A\times\varepsilon_{amp})}{\left(A^2\times B_{max}\times\varepsilon_{amp}^2\times R^3+\frac{E_{elec}^2\times B_{max}}{R}-2\times E_{elec}\times B_{max}\times A\times\varepsilon_{amp}\times R\right)^2}\\&=2\times\varepsilon_{amp}+\frac{2\times P_{TX}\times E_{elec}\times\varepsilon_{amp}\times(3\times A^2\times\varepsilon_{amp}^2\times R^4-E_{elec}^2-2\times E_{elec}\times A\times\varepsilon_{amp}\times R^2)}{\left(A^2\times B_{max}\times\varepsilon_{amp}^2\times R^3+\frac{E_{elec}^2\times B_{max}}{R}-2\times E_{elec}\times B_{max}\times A\times\varepsilon_{amp}\times R\right)^2\times\frac{R^2}{B_{max}}}\end{aligned} \tag{28}$$

By observing the above expression (28), we find that if

$$3\times A^2\times\varepsilon_{amp}^2\times R^4-E_{elec}^2-2\times E_{elec}\times A\times\varepsilon_{amp}\times R^2 \tag{29}$$

is greater than 0, (28) will be identically greater then 0. Hence, with the help of (27), (29) is transformed as

$$\left(G_rG_t\left(\frac{\lambda}{4\pi d}\right)^2\times\varepsilon_{amp}\times R^2\right)\times\left(3\times G_rG_t\left(\frac{\lambda}{4\pi d}\right)^2\times\varepsilon_{amp}\times R^2-2\times E_{elec}\right)-E_{elec}^2 \tag{30}$$

With the help of the constraint in (24), we have

$$G_rG_t\left(\frac{\lambda}{4\pi d}\right)^2\times\varepsilon_{amp}\times R^2>E_{elec} \tag{31}$$

To multiply both sides of (31) by 3, we have

$$3\times G_rG_t\left(\frac{\lambda}{4\pi d}\right)^2\times\varepsilon_{amp}\times R^2>3\times E_{elec} \tag{32}$$

To subtract $2\times E_{elec}$ from both sides of (32), we have

$$3\times G_rG_t\left(\frac{\lambda}{4\pi d}\right)^2\times\varepsilon_{amp}\times R^2-2\times E_{elec}>E_{elec} \tag{33}$$

By multiplying (31) by (33), we have

$$\left(G_r G_t \left(\frac{\lambda}{4\pi d}\right)^2 \times \varepsilon_{amp} \times R^2\right) \times \left(3 \times G_r G_t \left(\frac{\lambda}{4\pi d}\right)^2 \times \varepsilon_{amp} \times R^2 - 2 \times E_{elec}\right) > E_{elec}^2 \tag{34}$$

Which proves that the expression (30) is identically greater then 0 by subject to the constraint (24) derived from constraint C1. Hence, (28), namely, the second-order derivative of the $Ind(R)$ is identically greater then 0 by subject to the constraint C1, which proves that the $Ind(R)$ is a concave function with respect to the $R$ within the constraint C1. Therefore, the $R$ value indicated in (25) makes the expression $Ind(R)$ reach to its minimum value. By considering the last constraint C3 and the problem P2 is solved as

$$R = \begin{cases} \sqrt{\dfrac{B_{max} \times E_{elec} + \sqrt{P_{TX} \times B_{max} \times E_{elec}}}{G_r G_t \left(\frac{\lambda}{4\pi d}\right)^2 \times B_{max} \times \varepsilon_{amp}}} & \text{if } R \text{ in } (25) \leq \sqrt{\dfrac{P_{t\_\max}}{\varepsilon_{amp} \times B_{max}}} \\ \sqrt{\dfrac{P_{t\_}\max}{\varepsilon_{amp} \times B_{max}}} & \text{if } R \text{ in } (25) > \sqrt{\dfrac{P_{t\_\max}}{\varepsilon_{amp} \times B_{max}}} > \sqrt{\dfrac{E_{elec}}{G_r G_t \left(\frac{\lambda}{4\pi d}\right)^2 \times \varepsilon_{amp}}} \\ \text{No solution} & \text{if } \sqrt{\dfrac{P_{t\_\max}}{\varepsilon_{amp} \times B_{max}}} \leq \sqrt{\dfrac{E_{elec}}{G_r G_t \left(\frac{\lambda}{4\pi d}\right)^2 \times \varepsilon_{amp}}} \end{cases} \tag{35}$$

**Algorithm 1** Resource allocation to minimize the energy cost for the DEINR's uplink data transmission

**Input** :

$d$ ← RF energy transmission distance, $\lambda$ ← 2.4 GHz wavelength
$G_t$ ← Transmission antenna gain, $G_r$ ← Receiving antenna gain
$E_{elec}$ ← Consumed energy in DEINR for receiving a single-bit EP
$B_{max}$ ← Typical bandwidth of the ZigBee based network
$\varepsilon_{amp}$ ← Path loss character (joule per bit per square meter)
$P_{TX}$ ← DEINR's transmission power for transmitting uplink data
$P_{t\_\max}$ ← Maximum transmission power of DEINT for transmitting EPs
$K$ ← the number of bits contained in the EP
$m$ ← the preset number of EPs for each RF energy transmission period

**Output** : $t_{EP}$, $t_{DP}$, $P_{DEINT}$

Let $temp\_R = 0$, $temp\_P_t = 0$
**if** $\sqrt{\frac{P_{t\_\max}}{\varepsilon_{amp} \times B_{max}}} \leq \sqrt{\frac{E_{elec}}{G_r G_t \left(\frac{\lambda}{4\pi d}\right)^2 \times \varepsilon_{amp}}}$ **then return** Fault
**else**
    $temp\_R \leftarrow \sqrt{\frac{B_{max} \times E_{elec} + \sqrt{P_{TX} \times B_{max} \times E_{elec}}}{G_r G_t \left(\frac{\lambda}{4\pi d}\right)^2 \times B_{max} \times \varepsilon_{amp}}}$
    $temp\_P_t \leftarrow \varepsilon_{amp} \times (temp\_R)^2 \times B$
    **if** $temp\_P_t \leq P_{t\_\max}$ **then**
        $P_{DEINT} \leftarrow temp\_P_t$
    **else**
        $temp\_R \leftarrow \sqrt{\frac{P_{t\_\max}}{\varepsilon_{amp} \times B_{max}}}$
        $P_{DEINT} \leftarrow P_{t\_\max}$
    **end if**
    $t_{EP} \leftarrow \frac{K \times m}{B_{max}}$
    calculate $t_C$ according to (12) and $temp\_R$
    $t_{DP} \leftarrow t_C - t_{EP}$ **return** $t_{EP}$, $t_{DP}$, $P_{DEINT}$
**end if**

Algorithm 1 is designed to find the optimal value of $R$ to solve the problem P2. Thereafter, it find the optimal values of $t_{EP}$, $t_{DP}$ and $P_{DEINT}$ to solve the problem P1 depends on the optimal $R$. It is a resource allocation algorithm which intends to minimize the energy cost for the DEINR's uplink data transmission. It allocates the optimal time length for the DEINT's RF energy transmission and the DEINR's uplink data transmission, and it configures the optimal transmission power for transmitting EPs (RF energy) in the DEIN system.

According to the primary process described in Algorithm 1, it firstly calculates the optimal value of $R$ basing on Equation (25). Thereafter, the optimal transmission power for transmitting EPs is calculated based on Equation (8). Then, it checks if the obtained value of transmission power exceeds the limit of the maximum transmission power the DEINT's RF power amplifier circuitry can set. If the calculated transmission power is subject to the value restriction, the calculated optimal transmission power will be returned. Otherwise, the maximum transmission power of the DEINT's RF power amplifier circuitry will be returned, and the optimal value of $R$ will be updated according to Equation (8) with the maximum transmission power ($P_{t_max}$). In the practical DEIN system, the number ($m$) of EPs and the number of bits ($K$) included in each EP are preset parameters. They determine the time length ($t_{EP}$) for transmitting the EPs to charge each DEINR in the DEIN system, which is also the duration time for the DEINT's transmission antenna to stay opposite to each DEINR. As time $t_C$ can be calculated according to Equation (12) with the optimal value of $R$, the optimal time length ($t_{DP}$) for each DEINR's uplink data transmission is therefore obtained and turned.

## 6 | PERFORMANCE EVALUATION AND NUMERIC RESULT

To evaluate the performance of the algorithm, five sets of simulation experiments are carried out. Different RF energy transmission distance is applied to the simulation experiments, which is from 0.4 to 0.8 m with a step of 0.1 m. In each individual experiment, the DEINT will transmit 15,000 EPs with the same (127) bit-length at each time when its transmission antenna is turned opposite to DEINR A or DEINR B. The remaining constant system parameters are listed in Table 2.

Figure 6 shows the maximum number ($D_{uplink}$) of bits can be transmitted as the uplink data with respect to the DEINT's transmission power ($P_{DEINT}$) when different RF energy transmission distance $d$ is applied. The uplink data is transmitted by a DEINR depends on its harvested DC energy by receiving 15,000 EPs. With the growth of $P_{DEINT}$, $D_{uplink}$ increases as the DEINT's transmission power increases, and therefore more energy is harvested for uplink data transmission. By contrast, with respect to the same $P_{DEINT}$, fewer uplink data can be transmitted when longer RF energy transmission distance $d$ is applied because longer $d$ bring more energy loss in the air, and the available RF energy is weakened for DEINR's receiving antenna. Therefore, less harvested energy only affords fewer uplink data to be transmitted.

Figure 7 shows the system's total consumed energy during a successful process of uplink data transmission with respect to DEINT's transmission power ($P_{DEINT}$) when the RF energy transmission distance $d$ changes in sequence. A

**TABLE 2** Constant system parameters for performance evaluation

| Notation | Value |
|---|---|
| $K$ | 127 bits |
| $m$ | 15,000 |
| $\varepsilon_{amp}$ | $1.0 \times 10^{-9}$ J/bit/m$^2$ |
| $B_{max}$ | 250 kbps |
| $E_{elec}$ | $1 \times 10^{-9}$ J/bit |
| $G_r$ | 14 dBi |
| $G_t$ | 14 dBi |
| $\lambda$ | $12.49 \times 10^{-2}$ m |
| $P_{t_max}$ | 2 W |
| $P_{TX}$ | 0.1155 W |
| $d$ | {0.4, 0.5, 0.6, 0.7, 0.8} m |

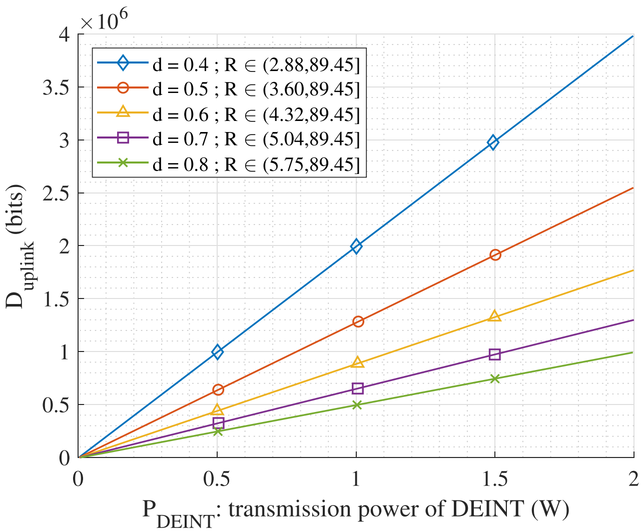


**FIGURE 6** The maximum number of bits ($D_{uplink}$) can be transmitted as the uplink data with respect to DEINT's transmission power ($P_{DEINT}$) when the RF energy transmission distance $d = \{0.4, 0.5, 0.6, 0.7, 0.8\}$ m

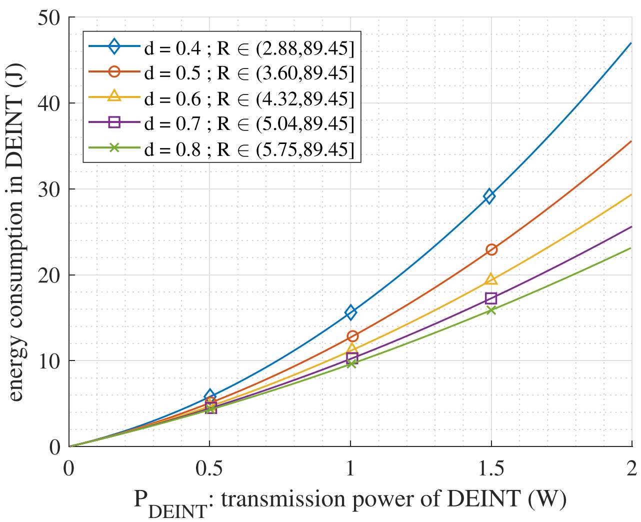


**FIGURE 7** The system's total consumed energy in the DEINT during an uplink data transmission process with DEINT's transmission power ($P_{DEINT}$) when the RF energy transmission distance $d = \{0.4, 0.5, 0.6, 0.7, 0.8\}$ m

successful process of uplink data transmission is from when the DEINT begins to transmit EPs for charging a DEINR to when the uplink data is successfully transmitted to the ZigBee coordinator. The total consumed energy is caused by transmitting 15,000 EPs and forwarding the uplink data from the DEINR to the ZigBee coordinator. When higher transmission power ($P_{DEINT}$) is used for the DEINT to transmit EPs and forward uplink data, it brings more energy consumption. Furthermore, according to Figure 6, higher $P_{DEINT}$ means more uplink data can be transmitted by the DEINR and then forwarded by the DEINT. Forwarding more uplink data also brings more energy consumption. As a result, the system's total consumed energy rapidly increases when $P_{DEINT}$ increases. By contrast, if $P_{DEINT}$ is fixed, less energy is consumed during the uplink data transmission process when longer $d$ is applied. Longer $d$ brings more energy loss in the air, which reduces the finally harvested DC energy. Therefore, less uplink data is forwarded by the DEINT, which weakens the total energy consumption.

Figure 8 shows the consumed energy per bit of the uplink data with respect to argument $R$ when different RF energy transmission distance $d$ is applied. The plots prove that $Ind(R)$ in Equation (15) is a concave function with respect to $R$. The reason for getting the concave curve can be explained by observing Figures 6 and 7. In the beginning, according to Equation (8), a slight increment of $R$ will generally increase the DEINT's transmission power and therefore increase the DEINR's harvested DC energy, which increases the amount of transmitted uplink data. Although the DEINT's energy consumption also increases, the growth speed of the transmitted uplink data is quicker than the total energy consumption. Hence, the system's consumed energy per bit of uplink data decreases in the beginning. With the increment of $R$, $P_{DEINT}$ increases quicker, and the growth speed of the DEINT's energy consumption becomes quicker than the transmitted uplink data. It is because more uplink data brings also more energy consumption for the DEINT to forward them. Hence, the system's consumed energy per bit of uplink data increases later.

Figure 9 shows the algorithm testing result when different RF energy transmission distance $d$ is applied. When the algorithm is applied, the system's consumed energy per bit of uplink data is minimized for every distance $d$. Only the optimal $R$ derived from the algorithm can achieve the best performance. Then, the optimal $R$ is used for calculating the transmission power ($P_{DEINT}$) and the time ($t_{DP}$) allocated for uplink data transmission.

Due to the massive RF energy attenuation in the air and the energy loss during RF to DC conversion, limited by the maximum transmit power, it is hard to use a longer distance in actual deployment in practice. But as the use of more realistic longer distance is a very important issue, we have carried out an additional simulation with longer distance. In Figure 10, We adjust the distance range from 5.4 to 5.8 m of Figure 9, we can still find that only the optimal R derived from the algorithm can achieve the best performance. Namely, the conclusion stays unchanged.

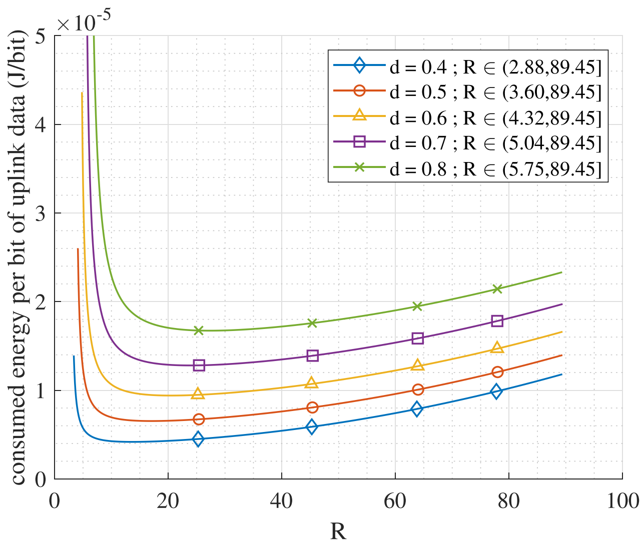


**FIGURE 8** The consumed energy per bit of transmitted uplink data with respect to argument $R$ when the RF energy transmission distance $d = \{0.4, 0.5, 0.6, 0.7, 0.8\}$ m

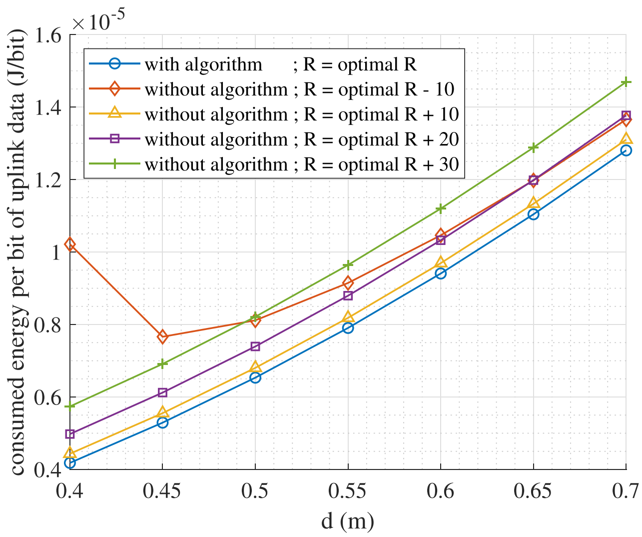


**FIGURE 9** The algorithm testing result with respect to different RF energy transmission distance $d$

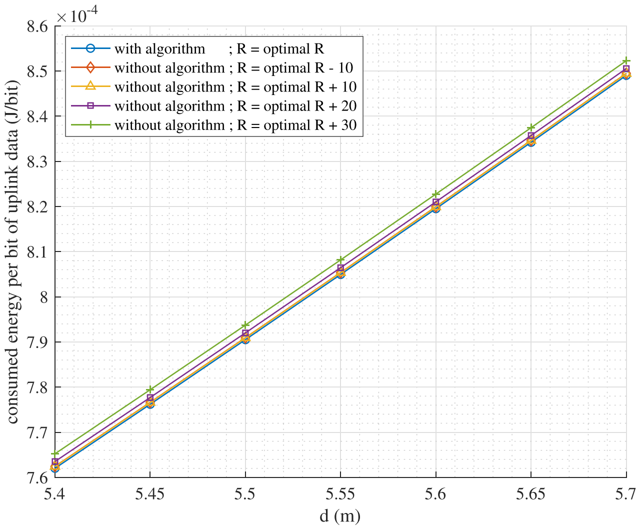


**FIGURE 10** The algorithm testing result with respect to different RF energy transmission distance $d$

## 7 | CONCLUSION

In this paper, a DEIN topology involving a single DEINT and multiple DEINRs has been proposed. Based on the topology, the energy estimation model has been designed. The model estimates the related energy during a process of transmitting and then receiving a $K$ bit-length EP. The estimated energy is the energy consumption in the DEINT, the transmitted RF energy, the inductive energy from the DEINR's receiving antenna, the energy consumption for receiving the $K$ bit-length EP and the finally harvested DC energy. Furthermore, a time allocation model has been designed for managing RF energy transmission and uplink data transmission in different time slots. The RF energy transmission is transmitting EPs to a DEINR, which is launched by the DEINT. The uplink data transmission is launched by a DEINR and routed by the DEINT to the smart gateway eventually. Based on the energy estimation model and time allocation model, a resource allocation algorithm has been designed to minimize the consumed energy per bit of uplink data. Finally, the numeric results obtained by the simulation experiments show that the energy consumption per bit of uplink data has been successfully minimized with the algorithm applied.


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## DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.


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