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Article

An Energy-Efficient Wireless Power Transmission-Based Forest Fire Detection System

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Abstract: Compared with the traditional techniques of forest fires detection, wireless sensor network (WSN) is a very promising green technology in detecting efficiently the wildfires. However, the power constraint of sensor nodes is one of the main design limitations of WSNs, which leads to limited operation time of nodes and late fire detection. In the past years, wireless power transfer (WPT) technology has been known as a proper solution to prolong the operation time of sensor nodes. In WPT-based mechanisms, wireless mobile chargers (WMC) are utilized to recharge the batteries of sensor nodes wirelessly. Likewise, the energy of WMC is provided using energy-harvesting or energy-scavenging techniques with employing huge, and expensive devices. However, the high price of energy-harvesting devices hinders the use of this technology in large and dense networks, as such networks require multiple WMCs to improve the quality of service to the sensor nodes. To solve this problem, multiple power banks can be employed instead of utilizing WMCs. Furthermore, the long waiting time of critical sensor nodes located outside the charging range of the energy transmitters is another limitation of the previous works. However, the sensor nodes are equipped with radio frequency (RF) technology, which allows them to exchange energy wirelessly. Consequently, critical sensor nodes located outside the charging range of the WMC can easily receive energy from neighboring nodes. Therefore, in this paper, an energy-efficient and cost-effective wireless power transmission (ECWPT) scheme is presented to improve the network lifetime and performance in forest fire detection-based systems. Simulation results exhibit that ECWPT scheme achieves improved network performance in terms of computational time (12.6%); network throughput (60.7%); data delivery ratio (20.9%); and network overhead (35%) as compared to previous related schemes. In conclusion, the proposed scheme significantly improves network energy efficiency for WSN.

Keywords: Forest fire detection; rechargeable wireless sensor networks; wireless mobile charger; power constraint; sustainable network lifetime

1 Introduction

During the past decades, fire was a serious threat to native forests in many parts of tropical and non-tropical developing countries. The risk of forest fire increases in extremely dry conditions, such as drought, and during high winds. Wildfires can disrupt transportation, communications, power and gas services, and water supply. They also lead to a deterioration of the air quality, and loss of property, crops, resources, animals and people.

Early fire detection plays a major role in saving the ecosystem and avoiding the waste of storage. In recent years, WSN-based forest fire detection systems have gained considerable attention due to monitoring of the potential risk areas frequently and an early detection of fire, which can significantly shorten the reaction time and also reduce the potential damage as well as the cost of firefighting [1].

In a forest fire detection-based WSN, a set of CO_2 sensor nodes monitor and record data on the physical conditions of the environment and forward the collected data to a central point [2,3]. The sensor nodes are equipped with wireless communication devices for communication with a base station (BS) either directly or via other sensor nodes [4–6]. Because the resources (battery, CPU, memory, etc.) of the sensor nodes are limited, energy conservation is one of the most critical issues affecting the applicability and lifetime of WSNs [4,7,8].

A number of recent studies have sought to improve energy conservation and maximize network lifetime [9–15]. One option is to utilize wireless mobile chargers (WMC), which move along the sensor nodes and recharge the nodes' batteries [16–19]. In such schemes, the WMCs receive energy from unlimited energy sources such as nuclear fusion, solar satellites, or wave farms [20,21]. Other efforts to improve WSNs have focused on reducing the implementation cost of the network by utilizing a BS equipped with an energy harvester device and a wireless charger [22]. In addition, the charging sequence of the nodes was optimized to enhance the quality of service, resulting in improved network performance. In addition, several related approaches have explored perpetual network operation utilizing WMCs. In rechargeable wireless sensor networks (RWSN), the WMCs are equipped with large, expensive energy harvesters [23,24]. Although utilizing WMCs can improve energy efficiency and maximize the network lifetime, large and dense networks require multiple WMCs, which is costly. In addition, in dense networks, the WMCs must move along nodes and meet them separately, leading to increased WMC travel time and reduced network performance. To address these limitations, multiple wireless power banks (WPB) can be used instead of expensive WMCs. In [25], a broker-based node recharging scheme (BNRS) that assigns a power bank to each cluster in order to enhance the network lifetime was presented. However, this scheme has high implementation costs in dense networks with many clusters. In addition, optimization of the locations of the WPBs to achieve charging coverage and promote network performance was not considered.

To address the limitations of previous works, in the present study we employ a small number of WPBs as mediators between the WMCs and sensor nodes. In the proposed scheme, energy for the power banks is provided via a WMC that moves along the power banks to recharge their batteries and is able to recharge itself via solar energy [26,27]. Moreover, we attempt to optimize the locations of the power banks such that the maximum number of nodes are covered. The WPBs are able to recharge the batteries of the nodes located within their charging ranges. In addition, a node-to-node energy transmission mechanism for charging nodes located outside the charging range of power banks is presented. Whereas, previous studies have not considered the ability of sensor nodes in RWSNs to receive and transmit energy wirelessly via RF technology [28], which would fully leverage the energy transmission properties of sensor nodes in RWSNs. Moreover, we utilize unmanned aerial vehicle (UAV) as the carrier of WMC since UAV is most proper for forest environment due to existence of dense obstacles between rechargeable devices. The main achievements of the proposed approach can be summarized as follows:

- Persistent network lifetime in forest fire detection-based WSNs is a vital issue, which has not been considered in most of previous studies. Therefore, in this paper, we attempt to achieve sustainable network operation using only one WMC and a small number of power banks.
- In most of previous WMC-based schemes, multiple WMCs are employed to recharge the sensor node which are belong to the large and dense networks. However, our ECWPT scheme is cost-effective for large, dense networks, as it employs WPBs instead of expensive WMCs.
- Most of previous works attempt to optimize the location of energy transmitters to enhance the energy efficiency, without considering their charging coverage issue. Therefore, the proposed ECWPT scheme attempts to optimize the locations of the WPBs to enhance the charging coverage and increase the number of recharged nodes.
- Unlike previous related works, the sensor nodes in ECWPT are able to exchange energy among themselves. Therefore, critical nodes with lower energy levels can continue to operate when WMCs are not immediately available to recharge their batteries. As a result, ECWPT achieves perpetual network operation.

The remaining sections are organized as follows: Section 1 gives an introduction. The literature review and system model are explained in Sections 2 and 3. The proposed algorithms are given in Section 4. Simulation results is presented in Section 5. Sections 6 and 7 give discussion and conclusion respectively.

2 Related Work

The discussion of the state of the art study is divided into two subsections, such as-(i) Forest fire detection-based systems, (ii) Wireless power transmission-based schemes.

2.1 Forest Fire Detection Systems

In the literature survey, it is found that a mobile ad hoc network (MANET) based forest-fires alert system has been presented in [29] which consists of MANET, wireless sensors, middleware software, and front-end web application. In [30], authors described how the burned area in the forest is predicted after a forest fire. Authors has used a genetic programming to develop an intelligent system on the basis of metrological data. A ZigBee based forest fire detection system has been introduced in [31] to early detect of forest fire. In IoT-based forest fire detection-based systems, the sensor nodes are equipped with limited power supplies and their energy depletion leads to late fire detection and reduce the network performance.

In the last decades, several energy-efficiency based forest fire detection systems have been designed to enhance the operation time of flame detectors. In [32], authors proposed an energy efficient data forwarding for forest fire detection using localization (EEFFL) technique. In that work, authors consider the energy limitation during data transmission process. To solve this problem, they use a semi-supervised classification model by dividing the forest area into different zones [High Active, Medium Active, and Low Active]. It is designed in such a way that it can be able to predict the state of the fire zone with 90% accuracy when only one parameter is sensed by sensor nodes due to energy constraints. In [33], an intelligent hybrid model has been designed for reliable and fast fire detection applied in WSN platform. This model discusses a data fusion strategy hybridized with an intelligent information routing system based on a clustering method of sensor nodes located in the vicinity of the event. The scheme proposed in that work guarantees the efficient energy consumption of the network which leads to a remarkable extension of its operation time. Furthermore, in [34] a fuzzy based unequal clustering and context-aware routing based on glow–worm swarm optimization scheme has been proposed. The aim behind such scheme is to prolong the operation time of fire detector sensors located throughout the network area. To this end, first, a fuzzy logic based unequal clustering is applied on the sensor nodes and then context aware routing procedure is used to enhance the energy efficiency of the network.

2.2 Wireless Power Transmission-Based Schemes

WPT is an interesting new area of research that has attracted increasing attention by academia and industry. In the context of WPT-based systems, several existing literatures have attempt to enhance the operation time of sensor nodes and prolong the network lifetime. The optimization of WMCs has been the focus of extensive attention. To balance the energy consumption of nodes and increase the operation time of the network, a charge time optimization of wireless mobile charger (CTOWMC) algorithm for optimizing the travel path of the WMC was introduced in [35]. In [36], a joint energy supply and routing path selection algorithm was designed to improve network performance and network lifetime by optimizing the path of the WMC based on energy consumption and remaining energy of nodes. In [37], energy efficiency and network lifetime were enhanced by optimizing the movement path and charging time at each charging location simultaneously, and an online charging node insertion algorithm providing improved network performance was introduced. In the same vein, a wireless mobile charger excursion optimization (WMCEO) algorithm was proposed in [38] to optimize the moving trajectory and charging time of the WMC in each sojourn location to achieve enhanced energy efficiency and network operation. In this scheme, the network area is divided into charging regions to achieve simultaneous recharging of nodes. The main contribution of [38] is joint consideration of the remaining energy of the nodes and the travel time of the WMC in WMC's tour optimization. The nearest-job-next preemption (NJNP) charging algorithm designed in [26] employs a WMC to charge the critical nodes with lower remaining energy. In NJNP, the closest node is selected as the next anchor point whenever a WMC receives charging requests from the nodes.

The energy-efficient cluster management-based scheme presented in [39] aimed to enhance energy efficiency and energy balancing by employing a BS that is able to transfer energy to the sensor nodes. In this scheme, cluster heads (CH) are selected according to the energy state of the member nodes, and the BS starts to recharge the CHs while collecting data from them. Similarly, to achieve a high charging rate and minimize energy consumption, a BS capable of simultaneously recharging and collecting data from nodes was utilized in [17]. First, the network topology was constructed by a clustering technique with the aim of balancing the number of clusters and the energy consumption of inter-cluster communication. Then, two modes of scheduling schemes for WMCs were presented that considered packet delay issues. A two-mode quality of service (QoS)-aware joint data collection and energy charging scheme was introduced in [40] to enhance network performance in terms of energy efficiency. Due to the NP-hardness of the proposed charging problems, they designed two heuristic charging schemes to solve charging problems with low complexity, i.e., a single-path scheduling scheme and multiple-path scheduling scheme. In [41], a fair energy division scheme (FEDS) was used in an attempt to achieve permanent network operation. To this end, two separate WMCs were employed to recharge the member nodes and CHs separately, and the energy level and energy-replenishment time of the WMCs were considered to optimize their movement path and charging time. A joint energy replenishment and data collection algorithm was presented in [17] for RWSNs. The main goal of this scheme was to achieve permanent sensor node operation. The WMCs acted as mobile sinks in the network, and their moving path was determined based on the shortest Hamiltonian cycle. Charging locations in the clusters were determined based on the energy distribution in each cluster by a static BS.

3 System Model and Assumptions

In the proposed ECWPT scheme, N number CO_2 sensor nodes are randomly dropped throughout the forest area from the flying machine (helicopter, airplane, etc.). The sensor nodes send their collected data toward a static BS deployed outside the network. In addition, M WPBs with high battery capacities are employed to recharge the batteries of sensor nodes located within the charging range (r) of the WPBs. The locations of the WPBs are optimized in the first part of the proposed scheme in order to maximize the number of covered nodes. In addition, a UAV is utilized which is responsible for moving along the WPBs and recharging their energy supplies. It is assumed that the WPBs are recharged continuously by the UAV, which guarantees that the energy of the WPBs is not depleted. Moreover, it is assumed that UAV moves to a charging station to recharge its battery after each charging cycle. The network model is depicted in Fig. 1. Because the sensor nodes equipped with RF technology, they can exchange energy among themselves. In fact, each node is able to receive and transfer energy to the nodes located inside its charging range. We use the charging model proposed in [42]. In charging WPBs, the UAV is the transmitter, and the WPBs are receivers. Furthermore, as the nodes are capable of exchanging energy among themselves, each node can be both a receiver and a transmitter. Consequently, the relation between received energy (Er) and transferred energy (Et) can be formulated as follows:

$$E_r = \frac{A_s A_r \eta E_t}{L_P}\left(\frac{\lambda}{4\pi (d+\beta)}\right)^2 \tag{1}$$

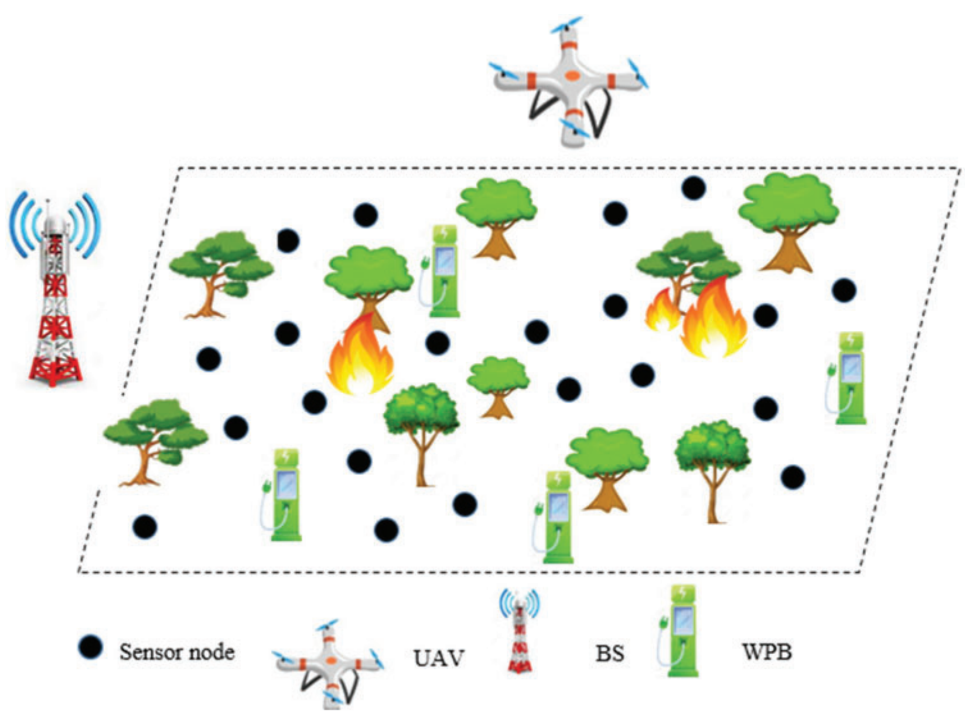

Figure 1: Network model

In the above equation, As and Ar are the transmitter and receiver antenna gain, respectively; η, LP and λ are the rectifier efficiency, polarization loss and wavelength, respectively; d is the distance between the receiver and transmitter; and β is a constant value employed to adjust the Friis free space equation for short-distance transmission [43]. Then, Eq. (1) can be rewritten as follows:

$$E_r = \frac{\mu}{(d + \beta)^2} \tag{2}$$

where,

$$\mu = \frac{A_s A_r \eta E_t}{L_P} \left(\frac{\lambda}{4\pi} \right)^2 \tag{3}$$

4 Energy-Efficient and Cost-Effective Power Bank-Based Recharging of Sensor Nodes Scheme

In the proposed ECWPT scheme, a small number of WPBs are employed to recharge the nodes located within their charging range (r). The proposed scheme consists of two mechanisms: power bank-based charging coverage enhancement (PBC2E) and node-to-node energy transmission (N2ET). The first attempts to optimize the locations of the WPBs to enhance the charging coverage of the power banks, while the second seeks to achieve permanent network lifetime by prioritizing the recharging of critical nodes that are not reachable by the WPBs. The following sub-sections describe the proposed C2EPB and N2ET mechanisms in detail.

4.1 Power Bank-Based Charging Coverage Enhancement (PBC2E) Mechanism

In the proposed approach, M number WPBs are deployed throughout the network area to receive energy from the UAV. WPBs are able to recharge the sensor nodes located within their charging range (r). Unlike previous related works [25], a limited number of WPBs are employed to achieve cost savings. As not all sensor nodes can be covered by the WPBs, the locations served by the WPBs must be optimized to ensure that the maximum number of sensor nodes are covered. We formulate this problem as an integer linear programming (ILP) problem.

In the proposed mechanism, a covered flag (CF) is assigned to each node. The CF value of a node can be 0 or 1 based on its coverage situation. The CF of a node will be 1 if it is located within the charging range of a WPB and 0 otherwise. Let Z be the set of available locations for deploying WPBs in the network area. Likewise, V= {v0, v1, . . . , vM } is the set of locations where power banks will be deployed. Then, V is optimized so that the maximum number of covered nodes (NCN) can be achieved (determined by Algorithm 1). The objective function of the proposed ILP can be formulated as follows:

$$\textit{Maximize}: NCN = \sum_{i=1}^{N} CF(i) \tag{4}$$

$$\textit{Subject to}: CF \in \{0, 1\}$$

$$V \in Z$$

After deployment at the optimal locations, the WPBs will broadcast query packets throughout the network, and the nodes that receive the packets will send their location information to the WPBs. The Euclidean distances between the nodes and WPBs are calculated in order to determine which nodes are located within the charging range of the WPBs (see Algorithm 1). The CF values of the identified nodes are subsequently changed to 1, and they start to receive energy from their respective WPBs. In addition, if any node is located within the charging range of multiple WPBs, it will receive energy from the closest WPB.

Algorithm 1: Determine Number of Covered Nodes

Input: CF: Covered Flag
R: charging range of WPB
N: number of nodes
V: {(X0, Y0), (X1, Y1), … (XM, YM)}//set of locations of WPBs
M: number of WPBs
Output: NCN: Number of Covered Nodes

1. For i = 1: N
2. CF (i) = 0
3. Endfor
4. For i = 1: N
5. node (i) sends its location (xi, yi) to BS
6. For j = 1: M
7. $D = \sqrt{(X_j - x_j)^2 + (Y_j - y_i)^2}$
8. If D ≤ r
9. CF (i) = 1
10. EndIf
11. EndFor
12. EndFor
13. For i = 1: N
14. NCN = NCN + CF
15. EndFor
16. Return NCN

4.2 Node-to-Node Energy Transmission (N2ET) Mechanism

In this work, WPBs can only charge nodes located within their charging range; nodes that are outside this range will not receive energy, and their energy will eventually be depleted which leads to a disaster in forest area. To overcome this limitation, in this scheme the sensor nodes located inside the charging range of the WPBs function as energy brokers between the energy transmitters and energy receivers. The energy receiver nodes will recharge the nodes located inside their charging range, and this process will continue until all nodes deployed in the network area are recharged.

In the proposed mechanism, a recharged flag (RF) is assigned to each node. The RF value of a node can be 0 or 1 based on its recharging situation. At the beginning of a charging cycle, the RF value of all nodes is 0. Whenever a node receives energy, its RF value is 1. All sensor nodes send their location information to the static BS, which then determines the value of n for each WPB according to the locations of the nodes around the WPB and the charging range of the WPBs. The sensor nodes can receive energy during a charging cycle T, which consists of n + 1 sub-cycles {T0, T1, … , Tn} as shown in Fig. 2. In the first sub-cycle (T0), the WPBs send request packets toward the nodes located within their charging range, and the nodes that receive the request packets send their required energy level to the WPBs. The required energy level is determined as follows:

$$ReqEnergy(i) = IniEnergy(i) - RemEnergy(i) \tag{5}$$

where IniEnergy and RemEnergy denote the initial energy level and remaining energy level of the node. The WPBs then start to recharge the nodes according to the required energy values received.

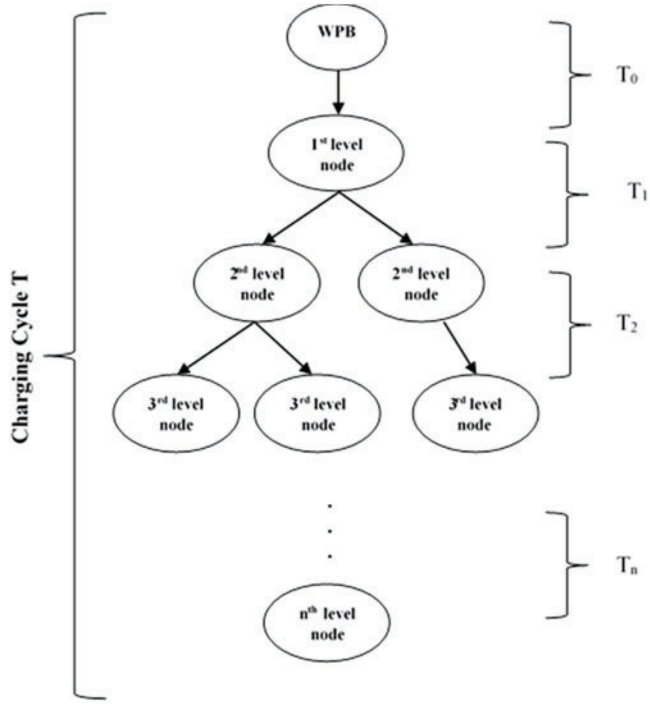

Figure 2: A charging cycle

In the next sub-cycles (T1-Tn), the sensor nodes located at the ith level check their charging range (y) and send a request packet to those nodes located inside their charging range that have not received energy previously (RF = 0). Upon receiving the request packet, the nodes calculate their required energy level (Eq. (3)) and send it to the broker nodes. However, as the sensor nodes are equipped with limited batteries, the energy transmitter nodes have to check their remaining energy levels and save their required energy for consumption during the waiting time. The saved energy of the ith node is calculated as follows:

$$SaveE(i) = WT(i) * ECon(i) \tag{6}$$

where Econ is the energy consumption level of a node at each time unit and WT is the waiting time required for the ith node to receive energy from a higher-level energy transmitter during a charging cycle. WT is calculated as follows:

$$WT(i) = \sum_{J=0}^{i-1} T_j + \sum_{j=i+1}^{n} T_j \tag{7}$$

In the above equation, n is the last level of the node deployment, which is determined by the static BS at the beginning of the network operation. The amount of available energy that can be transferred to the other nodes is calculated as follows:

$$AvailableE(i) = RemEnergy(i) - SaveE(i) \tag{8}$$

The total required energy of the nodes is calculated as follows:

$$TotalRE(i) = \sum_{j=1}^{k} ReqEnergy(j) \tag{9}$$

where k is the number of nodes that need to be recharged by the ith broker node. Two conditions are possible: (1) the available energy level of the ith node is equal to or greater than the total energy required to recharge the nodes, or (2) the available energy level of the ith node is less than the energy required to recharge the nodes. In the first condition, broker nodes start to recharge the normal nodes according to their required energy levels. However, in the second condition, the available energy of the broker nodes will be divided among the nodes according to their demand ratios. In other words, each energy receiver node will receive a percentage share of the available energy of the energy transmitter node, which is determined as follows:

$$PRCShare(j) = \frac{ReqEnergy\ (j) \times 100}{TotalRE} \tag{10}$$

Then, the jth node's share of the available energy of the broker node is given by the following:

$$Share(j) = \frac{PRCShare(j) \times AvailableE}{100} \tag{11}$$

Finally, the broker node starts to transmit energy to the nodes according to their energy share. Once the node is recharged, its RF value will change to 1. Any node that cannot be covered by any other nodes (RF = 0) will be recharged directly by the UAV. The details of the proposed mechanism are given in Algorithm 2.

Algorithm 2: Node-to-Node Energy Transmission Algorithm

Input: RF: Covered Flag
N: number of nodes
M: number of WPBs
n: level of nodes around WPBs
r: charging range of WPBs
(X, Y): location of WPBs

For i = 1: N
  RF (i) = 0
Endfor
For i = 1: N
  node (i) sends (xi, yi) to the BS.
  BS determines n
  For j = 1: M
    $D = \sqrt{(X_j - x_i)^2 + (Y_j - y_i)^2}$
    If D ≤ r
      CF (i) = 1

(Continued)

Algorithm 2: Continued

```
    EndIf
  EndFor
  EndFor
  While there is no dead node Do
    Cycle = Cycle + 1
    For i = 1: N
     If CF (i) == 1
       node (i) determines the ReqEnergy Eq. (3)
        node (i) sends ReqEnergy to respected WPB
        WPB send ReqEnergy level energy to node (i)
     EndIf
    EndFor
    For i = 1: n //Level
      For j = 1: N
       If CF (i) == 1
          node (i) sends request packet to range y
          For z = 1: N
          If node (z) receives request packet and RF = 0
             node (z) determines the ReqEnergy Eq. (3)
             node (z) sends ReqEnergy to node (i) Eq. (7)
             TotRE = TotRE + 1
             sum = sum + 1
          EndIf
         EndFor
         node (i) determines the AvailableE Eq. (6)
         If TotRE ≤ AvailableE
           For z = 1: sum
              node (j) send ReqEnergy energy to node (z)
           EndFor
         Else If
              For z = 1: sum
                Determine PRCShare (z) Eq. (8)
                Determine Share (z) Eq. (9)
                node (j) send Share (z) energy to node (z)
              EndFor
          EndIf
         EndIf
      EndFor
   EndFor
```

5 Simulation Results

In this section, the performance of the proposed scheme is analyzed and evaluated in comparison with the techniques introduced in [26,38] and [35], which were designed with the aim of enhancing network lifetime. The proposed scheme is simulated using OMNeT++, an object-oriented modular discrete event network simulation framework that is widely used in the research community and network communication due to its flexible and modular design.

Throughout the network area, 100–500 heterogeneous sensor nodes are randomly deployed. In the proposed scheme, the UAV moves along the WPBs at a speed of 0.5 m/s. Other relevant parameters are shown in Tab. 1. The simulation parameters for Physical (PHY), Medium Access control (MAC), transport and network layer are defined in Tabs. 2 and 3 defines the notations.

Table 1: Relevant parameters

Parameter	Value
Number of nodes	100∼500
Network area	1000 m × 1000 m
Packet size	128 bit
Initial energy of nodes	0.5 J
Energy dissipated in op-amp	0.0013e-12
Eelec	50e-9
Number of power banks	2∼5
Capacity of power banks	200 J
Velocity of WMC	0.5 m/s

Table 2: PHY, MAC, network and transport layers parameters

Parameter	Value
MAC	IEEE 802.15.4
Transport layer protocol	UDP
Antenna	Omni-directional
Propagation model	Two ray ground
Channel Bandwidth	11 Mbps

Table 3: List of notations

Notation	Describe
As	Transmitter antenna gain
Ar	Receiver antenna gain
H	Rectifier efficiency
Et	Transferred energy
Lp	Polarization loss
B	A constant value to adjust the Friis free space equation for short-distance transmission
D	Distance between receiver and transmitter
Λ	Wavelength

(Continued)

Table 3: Continued

Notation	Describe
NCN	Number of covered nodes
T	A charging cycle
WT	Waiting time
CF	Covered flag
RF	Recharged flag
ReqEnergy	Required energy level
iniEnergy	Initial energy level
RemEnergy	Remaining energy level
SaveE	Saved energy level
ECon	Energy consumption level of a node
AvailableE	Available energy level
TotalRE	Total required energy
PRCShare	Percentage share of a node in the available energy of the broker node
Share	Share of a node in the available energy of the broker node
r	Charging range of a WPB
y	Charging range of a node

Fig. 3 depicts the average remaining energy of the nodes after a charging cycle under different configurations. A direct relationship between the number of WPBs and average remaining energy of the nodes can be observed. In a low-density network, increasing the number of WPBs does not affect the average remaining energy of the nodes; however, in a high-density network, choosing a high number of WPBs enhances the performance of the proposed ECWPT scheme.

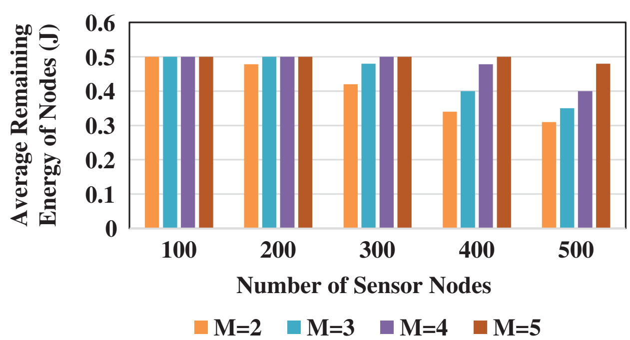

Figure 3: Average remaining energy of the nodes *vs.* the number of WPBs

The ECWPT scheme and the three previous approaches are compared in terms of the number of active nodes as time increases in Fig. 4. Despite using a UAV, the previous approaches provide limited network lifetime. By contrast, our proposed scheme achieves perpetual network lifetime with only one UAV thanks to the N2ET mechanism, which enables sensor nodes to receive energy from neighboring nodes. In other words, in the proposed mechanism, all nodes can be recharged even if they are not located within the charging range of a WPB or UAV.

Fig. 5 illustrates the computational time, defined as the running time of the mechanism, of the four different approaches as the number of nodes increases. The computational time of ECWPT is clearly shorter than those of the three other schemes, which spend a remarkable length of time determining the movement pattern of the mobile agents. Our proposed scheme shortens the computational time because the UAV moves along a predefined path to recharge the WPBs.

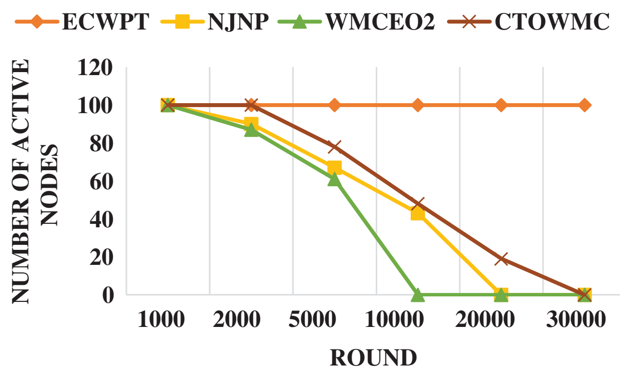

Figure 4: Number of active nodes *vs.* elapsed rounds

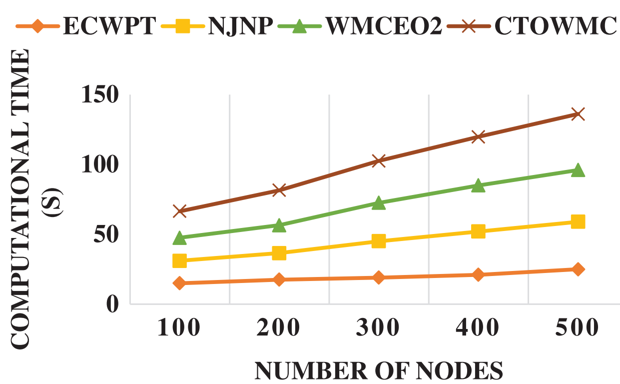

Figure 5: Computational time *vs.* the number of nodes

The total travel paths of the UAV in the four different approaches under high and low node densities are shown in Fig. 6. Increasing the number of nodes does not increase the travel time of the UAV in our proposed scheme, as the UAV meets only WPBs. Consequently, the travel path of the ECWPT scheme is shorter than those of the three other schemes because broker devices (WPBs) are utilized between the UAV and sensor nodes. On the contrary, in the other schemes, the WMCs have to move along sensor nodes and meet them separately.

Fig. 7 depicts the total remaining energy of the nodes after a charging cycle in the four different schemes. The remaining energy of the nodes is higher in our proposed scheme than in the other approaches thanks to the PBC2E mechanism, which increases the number of nodes recharged directly by WPBs. In the previously reported schemes, only critical nodes with lower residual energy receive energy from the WMC.

As shown in Fig. 8, the ECWPT scheme has a lower network overhead than the other schemes as the number of nodes increases. The NJNP, WMCEO2, and CTOWMC schemes induce additional network overhead due to the need to optimize the movement path and charging locations of the mobile devices.

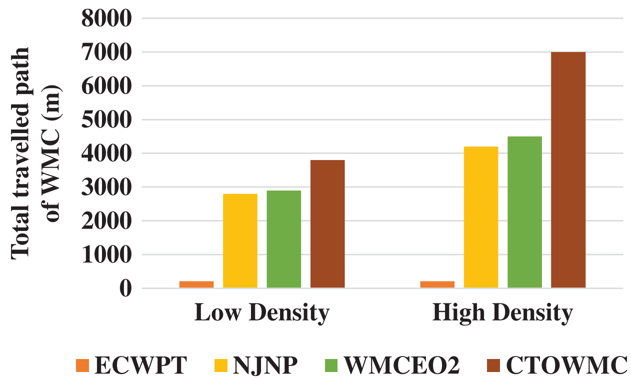

Figure 6: Total travel path of the UAV *vs.* node density

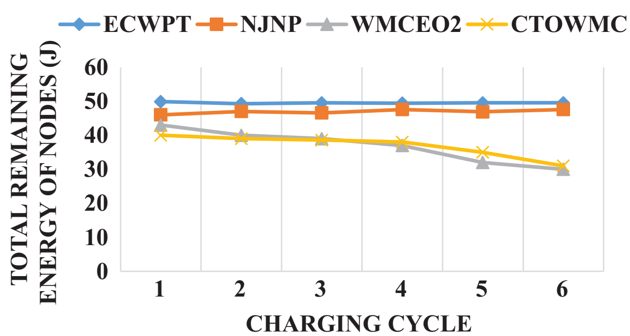

Figure 7: Total remaining energy of the nodes *vs.* charging cycle

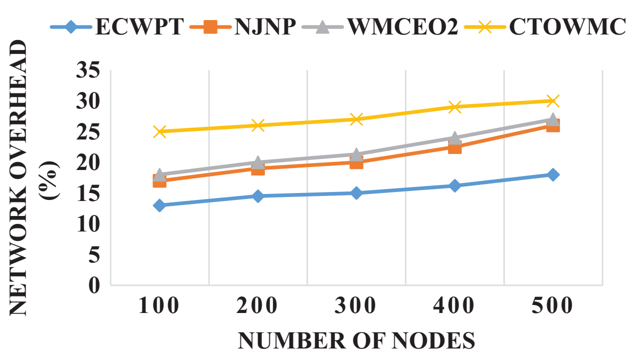

Figure 8: Network overhead *vs.* the number of nodes

Fig. 9 illustrates the data delivery ratios of the four different approaches as the number of nodes increases. Increasing the operation time of the nodes clearly leads to better network performance in terms of the data delivery ratio. The ECWPT scheme outperforms the other schemes in terms of the data delivery ratio, as the proposed scheme has a longer lifetime. The system throughputs of the four approaches as the number of nodes increases are depicted in Fig. 10. In terms of the recharging system, the throughput of the charging process is defined as the number of nodes that can receive energy during a given time period. Our proposed approach can recharge more nodes during a given time period than the previous schemes. This increase is due to the N2ET mechanism, which allows the sensor nodes to receive energy without waiting for the UAV to arrive at their location.

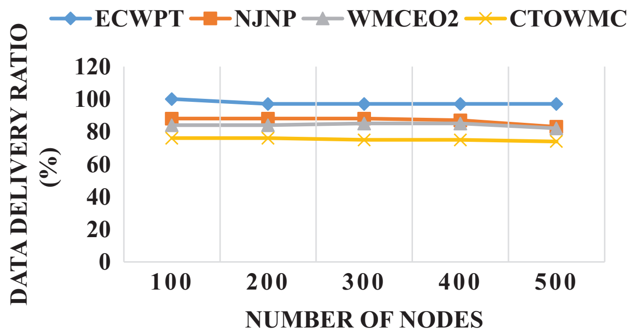

Figure 9: Data delivery ratio *vs.* the number of nodes

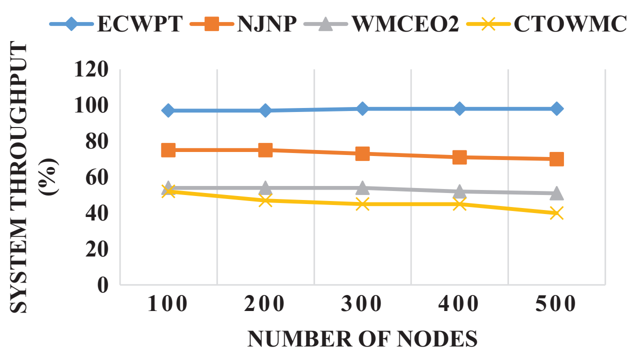

Figure 10: System throughput *vs.* the number of nodes

6 Discussion

Recently reported technological growth in wireless sensor network (WSN) has extended its application in forest fire detection and monitoring systems [44]. One of the most concerned issues in forest fire detection based WSNs is energy constraint of sensor nodes, which leads to late fire detection. Therefore, it is vital to discover a feasible solution to overcome the energy limitation problem in forest fire detection systems. A number of recent studies have sought to solve the energy limitation problem of WSNs [45–47]. Many have focused on energy efficiency by utilizing wireless mobile chargers to recharge sensor nodes. However, because wireless mobile chargers are equipped with expensive energy-harvesting technology, employing multiple chargers increases the network implementation cost. The network cost can be reduced by adopting broker power banks. Wireless static power banks were first used by Gharaei et al. in [25]. In these schemes, the power banks act as brokers between the WMCs and sensor nodes. However, a power bank is assigned to each cluster without optimizing residence locations, which is neither affordable nor feasible in dense, large networks. Therefore, in this paper, we propose an energy-efficient and cost-effective wireless power transmission scheme that employs a limited number of power banks and optimizes their locations in the network to enhance the number of covered nodes. likewise, we utilize an UAV which is responsible to move along and recharge their batteries frequently. In the proposed scheme, each node is assigned a CF to show its coverage situation. If a node is covered by a power bank, its CF will be 1; otherwise it will be zero. We then attempt to maximize the number of covered nodes using an ILP-based formula. In addition, to recharge nodes located outside the charging range of the power banks, we propose a node-to-node energy transmission mechanism that enables the sensor nodes to receive and transmit energy among themselves. In this mechanism, we define a charging cycle consisting of n + 1 sub-cycles (T0-Tn). In the ith sub-cycle, the nodes located in the ith level are responsible for recharging the nodes located inside their charging range. Simulations using OMNet++ show that the proposed ECWPT scheme outperforms previously reported approaches, as it achieves permanent network lifetime with minimum cost.

7 Conclusion

In this paper, we presented an energy-efficient and cost-effective wireless power transmission (ECWPT) scheme with the aim of achieving perpetual operation of forest fire detection based WSNs, which leads to early detection of wildfire and reduce the storage wasting. The proposed scheme utilizes a small number of power banks to transfer the recharging duty from energy transmitter to broker power banks, leading to enhanced network performance and reduced implementation costs. Likewise, an UAV-enabled wireless power bank has been employed to move along WPBs and recharge their batteries wirelessly. The proposed scheme consists of two mechanisms: PBC2E and N2ET. First, PBC2E optimizes the residence locations of the WPBs such that the maximum number of nodes are covered. Second, N2ET allows the sensor nodes to receive energy from each other, enabling energy to be transferred to critical nodes that cannot be reached by charging devices, leading to permanent network lifetime. Simulations comparing our proposed scheme with NJNP, WMCEO2, and CTOWMC show that our ECWPT scheme achieves sustainable network operation. Moreover, future studies will seek to optimize the number of power banks, which is currently undefined.

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