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# ECO-UDC: AN ENERGY EFFICIENT DATA COLLECTION METHOD FOR DISASTER AREA NETWORKS

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**Abstract:** After disasters, communication infrastructures in disaster-affected areas may fail due to physical damages or power outages. Unmanned aerial vehicles (UAVs) can act as flying base stations to satisfy the communication requirements of people in disaster-affected areas. For the purpose of increasing the data transmission rate and saving energy consumption of wireless telecommunication terminals (WTs), UAV mobility can be exploited to provide good channel conditions between UAVs and WTs. In this paper, a UAV with path length limitation is considered to provide communication service to WTs in a disaster area, a part of WTs can communicate with the UAV directly, and other WT communication with the UAV indirectly through D2D relay transmissions to reduce the UAV path length. Aiming at decreasing the total energy consumption of WTs, a novel UAV-aided data communicate method, ECO-UDC, is introduced. Extensive simulations demonstrate that ECO-UDC can reduce the energy consumption of WTs by approximately 30% - 40% compared to the benchmark method.

## 1 Introduction

At disaster-affected areas, people including victims and rescue team members usually want to use their wireless telecommunication terminals (WTs) to communicate with the outside world. However, communication infrastructure may be crippled due to physical damages or power outages. Lack of information flow could cause delay to rescue and recovery operations. As a solution to the issue, unmanned aerial vehicles (UAVs) have been given increasing attention by research communities to provide emergency communication services to disaster-affected areas [1, 2]. UAVs can serve as flying base stations to provide wireless communications to disaster affected areas. Owing to the mobility, a UAV can provide wireless communication services to WTs in a large disaster affected area.

Some applications about UAV-aided data communications were presented in the works in [3-6]. Those works mainly considered wireless sensor networks with usually small and fixed data size at the level of several kilo-bits per data collection period. On the other hand, our work presents the data collection from WTs of victims and rescue team members in disaster affected areas, where the data size is assumed varying and at the level of several million-bits. When the data size increases, a fast moving fixed wing UAV is unsuitable to provide communications due to the transient communication link lifetimes between the UAV and WTs. Therefore, we consider a scenario where a rotary wing UAV provides communications to WTs. WTs usually consume more energy for uplink communications than downlink communications and people in disaster-affected areas usually want to save the energy of their WTs; therefore, we consider UAV-aided data collection in this paper.

In this paper, we focus on a UAV-aided data collection technique aiming at decreasing the total energy consumption of WTs. A UAV usually has a maximum allowed flight length due to its battery energy capacity limitation. Therefore, it may be impossible for a UAV to visit all the WTs and collect data from them directly, and relay transmissions of few hops for some WTs become necessary. However, relay transmissions bring additional energy consumption of WTs. Therefore, the UAV path should be optimized to save the energy consumption of WTs.

The contributions of our work are summarized as follows. First, we analyze the UAV-aided data collection from WTs, and graph theory is utilized to model the optimization problem of decreasing the total energy consumption of WTs. Second, we propose a novel UAV-aided data collection method, ECO-UDC, including WT cooperative relay and UAV path planning to reduce the total energy consumption of WTs and satisfy the UAV flight length limitation. At last, we conduct extensive simulation to show that the proposed data collection method achieve better performance compared with the benchmark method.

The remainder of the paper is organized as follows. In Section II, we introduce the related works. Section III describes the scenario of the UAV-aided data collection. In Section IV, we model the reduction of WTs' energy consumption as an optimization problem and show that the problem is NP-hard. Our heuristic data gathering algorithm, ECO-UDC, is presented at Section V. Simulation results are presented in Section VI. Finally, the paper is concluded in section VII.

## 2 Related works

There have been several works studying data collection by UAVs in wireless networks [3-6]. In [3], the authors considered resource allocation for data gathering by UAVs. A dynamic programming based algorithm was proposed to allocate bandwidth to WTs, aiming to achieve the maximum throughput from WTs to UAVs. In [4], a data collection method based on game theory aiming to improve network energy efficiency while satisfying fairness in the distribution of resource among WTs was proposed. In [5], the authors presented a heuristic algorithm for optimizing the average total energy consumed by the ground-based nodes in data collection applications with a UAV. In [6], the authors focused on detecting the locations of endangered species in large-scale wildlife area through UAV-aided wireless networks. A path planning approach for the UAV was proposed based on a Markov decision process. The above mentioned works used UAVs for data collection. However, they did not consider the path length limitation of the UAV.

In [7], a UAV path planning algorithm was proposed to create smooth paths for fixed-wing UAVs to collect data. However, they did not consider the cooperation among WTs, but they assumed that the UAVs visit all WTs directly. In [8], the authors analyzed UAV-aided wireless sensor networks. They jointly considered the energy consumption and bit error rate of the sensors and the UAV travel time, and a particle swarm optimization based algorithm was proposed. Their work considered to apply a fixed wing UAV to gather data with small size from sensors. On the other hand, our work considers to apply a rotary wing UAV to gather data with big size from WTs. In [9], a heuristic solution was proposed for UAV-aided wireless sensor networks to minimize the flight time of the UAV and maximize the network lifetime. However, the work considers fixed data size of each sensor and data relay among sensors is applied in clusters which are formed only based on distance. On the other hand, in our work, the data sizes of WTs are different and data relay among them is applied based on the distance and the data size of those WTs.

## 3 System model: UAV-aided data collection in disaster affected areas

We consider a scenario where a set of WTs, $M$, is randomly distributed in a disaster-affected area, as shown in Figure 1. Each WT, $m \in M$, wants to send its data to a nearby undamaged base station or an emergency base station. The data can be photos and videos taken by a rescue team member to illustrate the situation of disaster of different places, of which the data size is at the level of several million-bits. However, due to the large distances between the base station and WTs, directly sending big size data to the base station will consume a large amount of energy of WTs. Therefore, the WTs only send messages about their locations and communication requirements to the base station. Then, the base station designs a UAV path, broadcasts the path to WTs, and sends out a rotary wing UAV to collect data from those WTs to collect data from WTs and save the energy of WTs. To ensure that the UAV can find WTs at their reported locations, WTs within the UAV path should be immobile since they send their reports until have transmitted their data to the UAV. The UAV has a maximum allowed flight length due to its battery energy capacity limitation. Therefore, it may be impossible for a UAV to visit all the WTs and collect data directly from them. Those WTs which are within the UAV path and can transmit their data to the UAV directly are noted as set $M_d$. The WTs which cannot send their data directly to the UAV, noted as set $M_i$. WTs in $M_i$ have to send their data to other WTs in set $M_d$, and WTs in set $M_d$ act as relay nodes to relay the data of WTs in $M_i$ to the UAV. It is assumed that data aggregation is not utilized by relay nodes. In order to decrease the energy consumption of WTs to send data with big size to the UAV, the UAV flies and hovers above each WT in $M_i$ at a fixed height when collecting data from those WTs.

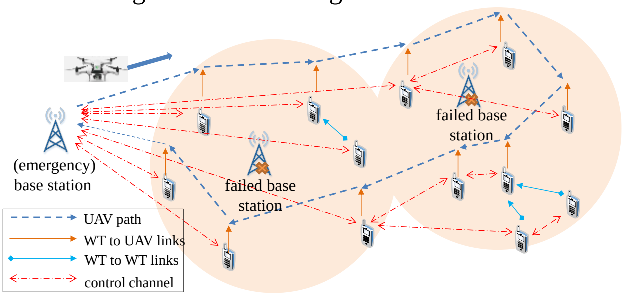


**Figure 1** The system model: UAV-based data gathering in WSNs

In this paper, we focus on the total energy consumption of WTs. In the remainder of the section, the data transmission model and the WT energy consumption model are described.

### 3.1 Data transmission model

For the links from WTs to the UAV and the links among WTs, it is assumed that the packets can be transmitted at different rates, which are determined by the channel condition such as signal to noise ratio (SNR) and bandwidth. To avoid interference among D2D links, before the UAV visits a WT $m_d$ in $M_d$, the UAV allocates resource to WTs which need to send their data to $m_d$ by D2D links. When the UAV hovers above a WT, only the WT beneath the UAV sends its data to the UAV so that there is no interference among the WT to UAV links. Since only a single active node transmits data at a given time, i.e., no interference source exists, the instantaneous $SNR_{ij}$ between two node $i$ and $j$ in a LOS channel is [10],

$$SNR_{ij} = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d_{ij}^{\alpha} N} \ , \tag{1}$$

where $N$ is the noise power, and $P_t$ is the transmission power. $G_t$ and $G_r$ are the gains at the transmitting and receiving nodes respectively. $\lambda$ is the wavelength, $d_{ij}$ is the distance between the two nodes, and $\alpha$ is the exponential path loss factor. According to [5], $\alpha$ could be applied with a value of 2.25 for WT to UAV links, and with a value of 3 for WT to WT links. Assuming the channel condition between any pair of WTs or between a WT to the UAV is unchanging during the transmission, the respective transmission rates could be calculated as follows,

$$R_{ij}(B, d_{ij}) = B \cdot log_2(1 + SNR_{ij}) \ , \tag{2}$$

where *i* and *j* can represent WTs and the UAV.

### 3.2 Wireless terminal energy consumption model

The energy consumption of WTs is composed of two parts, WTs in $M_d$ consume energy to send their data to the UAV directly, and WTs in $M_i$ consume energy to relay their data to other nodes.

In case of the energy consumption for transmitting WTs' data to the UAV, owing to data aggregation not used by relay nodes, the total amount of data transmitted from WTs to the UAV is fixed in each data collection round. Therefore, the total energy consumption of the WTs for sending their data to the UAV is fixed, which can be calculated as follows,

$$ED = \sum_{m \in M} D_m \cdot P_{WT} \,/\, R_{T2U}(B, d_{T2U}) \ , \quad (3)$$

where $D_m$ represents the data size of WT *m*, $P_{WT}$ is the transmission power of WTs, $R_{T2U}(B, d_{T2U})$ is the transmission rate between a WT to the UAV calculated by equations (1) and (2), *B* is the bandwidth, and $d_{T2U}$ is the distance between a hovering UAV and the WT below it.

The energy consumption for WT *i* to send its data to relay WT *j* can be calculated as follows,

$$ER_{ij} = D_i \cdot P_{WT} / R_{ij}\left(B, d_{ij}\right), \quad \forall i, j \in M, \quad (4)$$

where $R_{ij}\left(B, d_{ij}\right)$ is the transmission rate from WT *i* to its relay WT *j* as shown in equation (2), $D_i$ denotes the data size of WT *i*.

## 4 Optimization problem

The scenario of UAV data collection and data relay among WTs can be modeled as a graph $G(V, e)$, composed of $G_1(V, e_1)$ and $G_2(V, e_2)$. $G_1(V, e_1)$ describes the possible paths of the UAV for flying, and $G_2(V, e_2)$ describes the possible data relay among WTs. In Figure 2, solid red lines represent edges of $e_1$, and dashed blue lines represent edges of $e_2$. In both $G_1$ and $G_2$, *V* represents the set of WTs and a base station. $V=\{v_b, v1, v_2, \ldots, v_n\}$, where *n* is the number of WTs and $v_b$ is the base station. The weights of edges in $e_1$ represent the path lengths of the UAV for flying, which is denoted as $L_{ij}, ij \in V$. The weights of edges in $e_2$ represent the energy consumption of WTs for data relay, denoted as $ER_{ij}, ij \in V$.

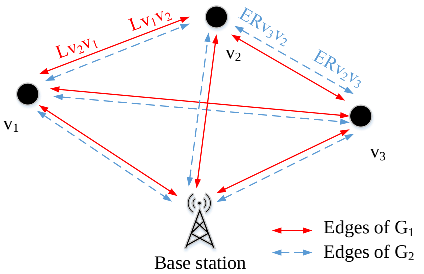


**Figure 2** The graph description of the data gathering of the UAV and data relaying of WTs

The optimization problem is reducing the total energy consumption of WTs for UAV-aided data collection, under the restraint of the UAV path length limitation, denoted as $L_{max}$. It can be formulated as follows,

$$\begin{aligned}
\textbf{Min} \quad & \textstyle\sum_{i \in v} \sum_{j \in v} y_{ij} \cdot ER_{ij} \quad (5)\\
\textbf{S.t.} \quad & \textstyle\sum_{j \in V} x_{ij} + y_{ij} = 1, \ \ \forall i \in V \\
& \textstyle\sum_{i \in V} x_{ij} < 1, \quad \forall j \in V \\
& \textstyle\sum_{i \in V'} x_{i,v_b} \cdot \sum_{j \in V'} x_{v_b,j} = 1 \ , \\
& \textstyle\sum_{i \in V} y_{ij} \cdot \sum_{i \in V} y_{ji} = 0, \ \ \forall j \in V \\
& \textstyle\sum_{i \in V} \sum_{j \in V} x_{ij} \cdot L_{ij} \leq L_{max} \ ,
\end{aligned}$$

where $x_{ij} = 1/0$ indicates the UAV travels/does not travel from *i* to *j*. $y_{ij} = 1/0$ means *i* sends/does not send data to *j*. $x_{i,v_b} = 1/0$ implies that the UAV travels/does not travel from WT *i* to the base station $v_b$. $x_{v_b,j} = 1/0$ denotes that the UAV travels/does not travel from the base station $v_b$ to WT j. *V'* represents the set of all the WTs. The objective function stands for minimizing the energy consumption of WTs for data relaying. The constraint 1 means that for every vertex *i*, it should be within the path of the UAV, i.e. $\sum_{j \in V} x_{ij} = 1$, or should send its data to a relay node, i.e. $\sum_{j \in V} y_{ij} = 1$. The constraint 2 indicates that every vertex should only be visited once or not by the UAV. The constraint 3 represents that the base station is within the path of the UAV. The constraint 4 means that only one-hop relay is allowed among WTs. The constraint 5 implies the path length of the UAV should not exceed the maximum allowed flight path of the UAV.

The predefined problem can be divided into two sub-problems. The first one is selecting a part of WTs and visiting them by the UAV directly, and the second one is finding the shortest path for the UAV to visit those selected WTs. The second sub-problem is a traveling salesman problem (TSP), which is NP-complete, and an exact solution is both hard and impractical to find [11]. Therefore, in the next section, we define a novel UAV-aided data collection method which utilizes a heuristic algorithm to solve the problem.

## 5 The novel UAV-aided data collection method: ECO-UDC

In this section, an Energy Consumption-Oriented UAV Data Collection (ECO-UDC) method is proposed. First, we assume the UAV visit all WTs, a temporary UAV path can be decided using [12]. The UAV path can be described as a set of *(n+1)* order pairs of WTs and the base station as follows,

$$K = (v_b, i_1), (i_1, i_2), \ldots, (i_n, i_b). \ \ i_1, i_2, \ldots, i_n \in V \quad (6)$$

Then, we calculate the benefit $B(i_z)$ of removing WT$i_z$ from the UAV path, and the benefit $B(i_z)$ can be calculated as follows,

$$B(i_z) = \frac{\textit{path length reduction of UAV by removing } i_z}{\textit{energy consumed by } \ i_z \textit{ to send data to a repeater}}, \quad (7)$$

where the energy consumption of $i_z$ can be calculated by equations (1), (2) and (4). The UAV path length reduction can be calculated by defining the updated UAV path. Assume there are $\mathrm{k} + 1 \leq \mathrm{n} + 1$ edges in the UAV path *K* shown as follows,

$$K = (v_b, i_1), (i_1, i_2), \ldots, (i_k, i_b). \ \ i_1, i_2, \ldots, i_k \in V \quad (8)$$

If $i_z, 1 \leq z \leq k$ is removed from the UAV path, it will be updated as follows,

$$K' = (v_b, i_2), (i_2, i_3), \ldots, (i_k, i_b), \quad if\ z = 1; \quad (9)$$
$$K' = (v_b, i_1), \ldots, (i_{z-1}, i_{z+1}), \ldots, (i_k, i_b), \ if\ 1 < z < k;$$
$$K' = (v_b, i_1), \ldots, (i_{k-2}, i_{k-1}), (i_{k-1}, i_b). \ if\ z = k$$

It should be mentioned that not all WTs can be removed from the UAV path *K*. A WT can relay the data of another WT only if the distance between them is smaller than the communication range of WTs. Therefore, the benefits of removing the WTs, which cannot find relay nodes from the UAV path, are set as 0.

At last, we remove the WT with the maximum benefit $B(i_z)$ from the UAV path until the UAV path length is not larger than $L_{max}$ or no WTs can be removed from *K*. The ECO-UDC method is shown in the pseudo-code of Algorithm 1.

**Algorithm 1** An Energy Consumption-oriented UAV Data Collection algorithm (ECO-UDC)

**Input:** $G(V,e) = G_1(V,e_1) \cup G_2(V,e_2), L_{ij}, ER_{ij}$
1: Assume the UAV visits all WTs, a temporary UAV path *K*, as shown in equation (6), can be decided.
2: $x_{ij}, y_{ij} = 0, for\ i,j \in V,$
3: $C(i) = 1, for\ i \in V, C(i)$ means if data of WT *i* can be relayed by other WTs.
4: **if** $\sum_{i\in V}\sum_{j\in V} x_{ij}L_{ij} \le L_{max}$ and $B(i_z)\cdot C(i_z) > 0$ **then**
5: Calculate the benefit $B(i_z)$ of removing WT $i_z$ from the UAV path *K* by equation (7)
6: Remove the WT $i_z$, with the biggest $B(i_z)\cdot C(i_z)$ value from the UAV path to update *K*.
7: Find the relay node of $i_z$, and denote it as $i_{zr}$,
8: $C(i_{zr}) = 0, y_{i_z, i_{zr}} = 1,$
9: **end if**
10: **if** $(i,j) \in K$ **then**
11: $x_{ij} = 1$
12: **end if**
Output: $x_{ij}y_{ij}, \ \forall i,j \in V$

As shown in line 4 of the pseudo-code, if the UAV path length limitation $L_{max}$ is small, the algorithm will stop with a UAV path longer than $L_{max}$, which means the UAV may not collect the data from all WTs due to flight length limitation. In the next section, the performance of the proposed method is evaluated.

## 6 performance evaluation

MATLAB has been used to construct the simulation platform. It is assumed that $n$ WTs are randomly distributed in an area of $H \times H(m^2)$. The data sizes of WTs are varying and the average value is $D_{ave}$. The details of the parameters are listed in Table I. The IEEE 802.11g standard is assumed to be used by the WT to WT links, and the data rate is listed in Table II [5], where an exponential path loss of 3 is applied. The proposed algorithm is compared with a distance-based cluster algorithm. In the benchmark algorithm, WTs form clusters based on distance. WTs within a special range $R_{cluster}$ of each other form clusters, cluster heads are randomly selected in clusters, and the UAV gathers data from the cluster heads.

**Table I** Parameters for simulation

| Parameters | value | Parameters | value |
|---|---|---|---|
| $H \times H$ | $1000 \times 1000m^2$ | $f$ | 2.4 GHz |
| $n$ | 50-150 | $B$ | 20 MHz |
| $D_{ave}$ | 2-10 Mbit | $d_{max}$ | 100 m |
| $P_{WT}$ | 0.2W | $R_{cluster}$ | 60 m |
| $R_{T2U}$ | 36 Mbps | $L_{max}$ | 10000 m |
| $d_{T2U}$ | 80 m | - | - |

**Table II** Data rates for 802.11g standard [5]
(with path loss exponents of 3, $BER \le 10^{-5}$)

| Rate(Mbps) | Distance(m) | Rate(Mbps) | Distance(m) |
|---|---|---|---|
| 54 | 20 | 12 | 54 |
| 48 | 24 | 9 | 57 |
| 36 | 35 | 6 | 65 |
| 24 | 42 | 2 | 77 |
| 18 | 51 | 1 | $d_{max}$ |

An example scenario is shown in Figure 3. In the scenario, there are 20 WTs represented by circles, and the gray level of the filling of each circle represents the data size of the WT. The blue dotted lines are the route of the UAV, and the red lines with arrow are relay links among WTs.

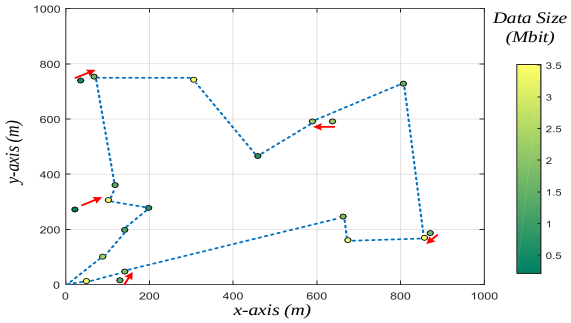


**Figure 3** An example scenario with the UAV route and the data relay route

The WTs' total energy consumptions for 1000 data collection rounds are shown in Figure 4 and Figure 5. In Figure 4, the numbers of WTs increase from 50 to 150, while the average data size is fixed as 2Mbit. In Figure 5, the number of WTs is fixed as 100, while the average data sizes increase from 2Mbit to 10Mbit. As shown in those figures, the WTs' total energy consumption is increasing with the number of WTs or the average data size of WTs. The proposed algorithm, ECO-UDC, can reduce the total energy consumption of WTs by approximately 30%-40% than the benchmark algorithm. This is because in ECO-UDC, we jointly consider the data sizes of WTs and the distances between WTs to form relay links among WTs. For the benchmark method, only the distances among WTs are considered to form clusters, but the data sizes of WTs are not considered. Therefore, in the benchmark algorithm, when the data size of a WT is large, it will cost the WT a lot of energy to send the data to its cluster head.

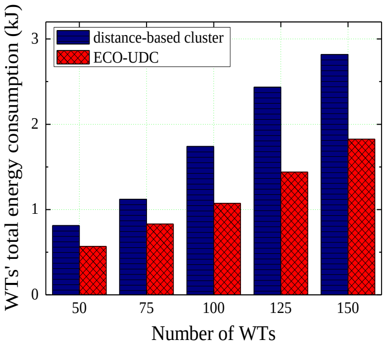


**Figure 4** WTs' total energy consumption v.s. number of WTs.

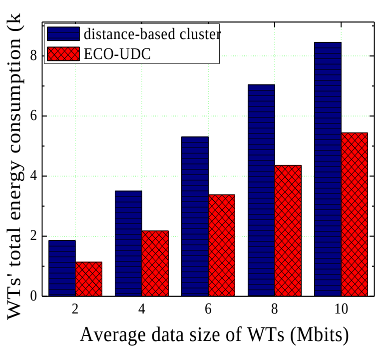


**Figure 5** WTs' total energy consumption v.s. average data size of WTs.

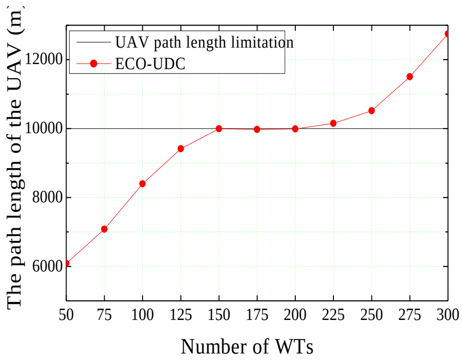


**Figure 6** The path length of the UAV v.s. number of the TWs.

The UAV path lengths versus the numbers of the TWs are plotted in the graph in Figure 6. As shown in the plot, when the number of WTs is below 200, the path lengths of ECO-UDC is smaller than $L_{max}$, which implies that the proposed ECO-UDC is suitable to the scenarios with less than 200 WTs in an area of $1000 \times 1000m^2$. If the number of WTs or the area increases, ECO-UDC needs a UAV with a larger path length limitation.

**Table III** Simulation time for the proposed method (with path loss exponents of 3, $BER \leq 10^{-5}$)

| Number of WTs | Time for TSP solver (ms) | Time for ECO-UDC (ms) |
|---|---|---|
| 10 | 5139 | 5141 |
| 50 | 6577 | 6631 |
| 100 | 8362 | 8568 |
| 200 | 12437 | 12341 |
| 500 | 25817 | 31526 |

We measure the CPU times for the proposed algorithm (for a scenario with 10-500 WTs and the average data size is 2Mbits) on a 64-bit Windows machine using an Intel CORE i7-5600U CPU @ 2.60 Ghz. As shown in Table III, the major computational cost is due to the solving of the TSP.

## 7 Conclusions

In this paper, we analyzed UAV data collection from WTs in disaster affected areas in an energy efficient way. Aiming at decreasing the total energy consumption of WTs and with the constraint of the path length limitation of the UAV, a novel UAV-aided data collection method, ECO-UDC, including WT cooperation and UAV path planning is introduced. The effectiveness of the proposed method was demonstrated by extensive simulations. In particular, simulation results showed that the proposed algorithm is able to reduce the energy consumption of the total WTs by approximately 30% to 40% in contrast with the benchmark method.

## Acknowledgements

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