Energy Efficient Data Gathering Algorithm in Hierarchical Wireless Sensor Networks with Mobile Sink

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Abstract- **One of the most critical issues in wireless sensor networks is the limited energy availability of the network nodes. This paper is investigating the advantages of using controlled sink mobility in clustered wireless sensor networks (WSNs) which increases network lifetime. In a clustered sensor network all Cluster Heads (CHs) have to transmit their buffered data to the sink during a specified interval, called data reporting time (t_{dr}). In this paper, we propose a scheme that prescribes the sink path for collecting all CHs data in t_{dr} time span while maximizing network life time using the mathematical model MILP (Mixed Integer Linear Programming). The proposed scheme is compared with other related schemes by means of various simulation scenarios. Simulation results show that the proposed scheme significantly outperforms other schemes.**

Keywords; mobile Sink; wireless sensor network, network's life time, energy aware algorithm.

I. INTRODUCTION

Wireless sensor networks have recently emerged as a new information-gathering paradigm with a diversity of applications. A WSN is typically composed of low-cost, low-power, densely-deployed and randomly distributed sensors [1]. Besides monitoring the environment by taking spatial or temporal measurements, sensors are also responsible for routing sensing data back to the sink [1-3].

Recently, sink mobility has become an important research topic in wireless sensor networks. Existing work shows that sink mobility can improve the performance of sensor networks [4-7]. On the other hand, hierarchical or cluster-based routing, are well-known techniques with special advantages related to scalability and efficient communication. As such, the concept of hierarchical routing is also utilized to perform energy-efficient routing in WSNs [8].

In this paper, we investigate the advantages of sink mobility in a clustered sensor network. In a clustered network, all sensors are grouped into a number of clusters. In which, specific sensors named cluster heads (CHs) have to collect the data of other cluster members. All CHs should report their received data to the sink during a period of time which is defined according to the sensor network's application. If CHs have boundless time for reporting their data to sink, the mobile sink has enough time to collect CHs data. Thus, the sink can come close to each CH and collect its data, in order to minimize CHs total transmission power. Unfortunately, in practical applications the mobile sink does not have much time to do so. Therefore, some other data collection method may used. This paper proposes a scheme based on mathematical models which can manage sink movements over limited data collecting time spans while maximizing total network lifetime at the same time.

The remainder of the paper proceeds as follows. We discuss about some related routing algorithms in section 2. In section 3, we will describe the sink mobility problem and the proposed algorithm. Finally, in section 4 efficiency evaluation of the mentioned algorithms is performed via simulations and the results are stated in details.

II. RELATED WORK

Several protocols have been proposed so far for data delivery by mobile sink in WSNs [9]. Luo and Hubaux [10] showed that the network lifetime can be extended significantly if the mobile sink moves around the periphery of WSN. They assumed that, if the mobile sink can balance the traffic load of the nodes, the network lifetime could be increased. Therefore, they proposed an optimization problem for choosing a mobility strategy that minimizes the maximum traffic load of the nodes. However, they assumed the shortest path routing, which, in general, does not produce the best lifetime and also it is not suitable for Cluster based Networks.

In [11], TTDD suggested to make up for the disadvantage of low energy-efficiency because all the sensors are involved in transmitting data. TTDD constructs a grid at the center of the source which has detected an event, and transmits data through sensors located on the crossing point. When a sink needs data, it initially looks for its neighboring local dissemination node. To do this, a sink performs regional flooding. Unfortunately, TTDD has a few defects. Firstly, whenever an event occurs, a grid is constructed at the center of the source. So if an event occurs simultaneously, the number of control packet which constructs a grid will increase, causing the energy of sensors to be consumed suddenly. Secondly, after a grid is constructed, it communicates through sensors located at the crossroad, their energy consumption is considerable.

In [12], a routing protocol, called MobiRoute, is suggested for WSNs with a path predictable mobile sink to prolong the network lifetime and improve the packet delivering ratio, where the sink sojourns at some anchor points and the pause time is much longer than the movement time. Accordingly, the mobile sink has enough time to collect data, which is different from our scenario.

In [8], the best location for BS is determined in a distributed manner. At the beginning of each round, clustering is performed and cluster heads (CHs) are selected. Then all CHs send a status packet across the network in which they propose a maximum distance they can support for data communication to BS. This distance is derived mathematically based on the nodes remaining energy and lifetime. The optimal point for BS's new location is where data communication is efficient for all CHs. A specific node makes the final decision after inspecting the energy efficiency of all CHs in the network for data communications to BS and then BS moves to the location of that node

III. PROPOSED ALGORITHM

Assume a network with a mobile sink and N sensors, $S_i, i = 1...N$,with the initial energy of $S_0^{e_0}$ are randomly distributed over the network region. The mobile sink can move freely from any point to another in a negligible time. This is similar to what is assumed in [9], [13].

In order to increase lifetime, clustering method in [8] is implemented. The operation of implemented algorithm is separated into two phases, the setup phase and the steady state phase which are all done during T_{round} time slot. In the setup phase all the sensors are divided into two groups, cluster heads (G^{CH}) and cluster members (G^{CM}) with $N.\rho$ and $N(1-\rho)$ members respectively; Where ρ is the desired percentage of cluster heads. In the steady state phase, the cluster members S_i^{cm} send data to their cluster head S_i^{ch} in TDMA (Time Division Multiple Access) based manner. Each CH buffers its received data and then sends it to the mobile sink with the rate of f_i (bit/second) The CHs can adjust their transmitting range (r). The time slot T_{round} , is separated to the following three parts.

$$T_{round} = t_{cf} + t_{dc} + t_{dr} \qquad (1)$$

Where, t_{cf} and t_{dc} are the Cluster Formation time and Data Collection time, respectively. During t_{dc} each CH collects the data from its CMs. Finally, t_{dr} is the Data Reporting time in which the CHs send their buffered data to the mobile sink. Note that unlike t_{cf} and t_{dc}, t_{dr} depends on the type of application. The mobile sink must collect all CHs' data during t_{dr}; otherwise some packets may be lost. The sink mobility varies depending on t_{dr}. Namely, if t_{dr} is very high, the mobile sink has enough time to collect CHs data. Thus it can come close to each CH and collect its data in order to minimize CHs total transmission power. In this case, t_{dr} is equal to the sum of all CHs data reporting times. Although the network lifetime is increased using this method but in real conditions there is not enough time for data collection. For this reason the CHs have to increase their transmission range in order to make two or more "range overlapped" areas. Therefore, the mobile sink can stay between two or more CHs and gather their data concurrently. In the case of very low t_{dr} time, CHs may increase their transmission range till the mobile sink can receive all CHs data from one location at the same time. In this case the mobile sink has to stay immovable and receive data until the CH of the biggest cluster send its all data. In fact, there is a trade-off between the minimization of data reporting time and total power consumption (lifetime maximization). In this paper, we propose a sink mobility scheme for collecting all CHs data in t_{dr} while minimizing the total power consumption at the same time. In other words, our algorithm determines the best sink path while each CH can freely change its transmission range (r_i) in order to maximize network lifetime (Fig. 1). We will solve the following problem via a mathematical modeling. In next section we describe the energy model we used for our scheme.

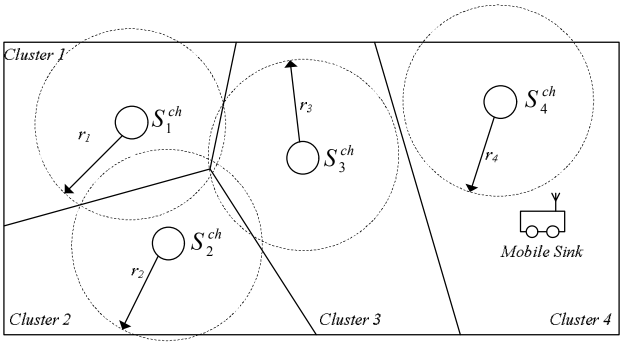

Fig. 1 A clustered wireless sensor network with a mobile sink.

A. Energy model

Suppose sensor node i transmits data to sensor node j with a rate of f_{ij} bit per second (bps). Then we model the transmission power at sensor node i as [9,13].

$$E_{ij}^{t} = c_{ij}.f_{ij} \qquad (2)$$

Where c_{ij} is the cost associated with link (i, j) and can be modeled as

$$c_{ij} = \theta_1 + \theta_2.d_{ij}^{\alpha} \qquad (3)$$

Where θ_1 and θ_2 are constants related to node energy dissipation to run the radio electronics and power amplifier in transmitter and α is the path loss factor and $2 \leq \alpha \leq 4$. d_{ij} is the physical distance between sensor nodes i and j. The power consumption at the receiving sensor node i can be modeled as [13]

$$E_i^r = \rho . \sum_{k \in N}^{k \neq i} f_{ki} \qquad (4)$$

Where f_{ki} (also in b/s) is the incoming bit-rate received by sensor i from sensor k and ρ is a constant coefficient.

In this paper, we assume that the interference from simultaneous transmissions can be effectively avoided by appropriate MAC layer scheduling. For low bit rate and deterministic traffic pattern considered in this paper, a contention- free MAC protocol is fairly easy to design and its discussion is beyond the scope of this article.[9,13]

B. Mathematical Formulation

We first define a Mixed Integer Linear Programming (MILP) analytical model to determine sink routes that maximizes the network lifetime.

The mobile sink is able to travel to K places P_j, $(j:1...K)$ and stay t_j, $(j:1...K)$ seconds at each place to receive CHs data. The location of P_j are defined such that at least one of the CHs members (G^{CH}) could be able to send its packets to mobile sink located in each P_j. In other words, each P_j must be within the transmission range (r_i) of one or more CHs.

Now we define the Locations Set V_i^{CH}, where a CH can send its packets to:

$$V_i^{CH} = \{P_j \mid D(S_i^{ch}, P_j) < r_i ; i = 1...\rho.N , j = 1..K\} \qquad (5)$$

Where $D(S_i^{ch}, P_j)$ is the Euclidean Distance between i-th cluster head, S_i^{ch}, and j-th sink location. For instance, Fig. 2 shows that three cluster heads, $S_1^{ch}, S_2^{ch}, S_3^{ch}$ that can totally cover 17 sink locations.

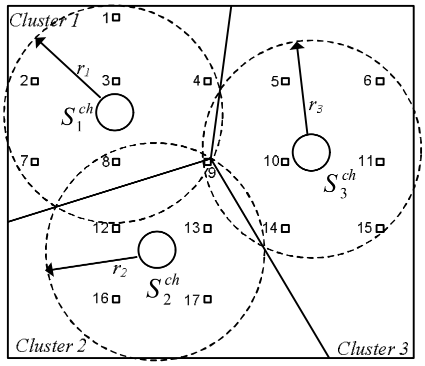

Fig. 2 Transmission range coverage of sink locations

For these CHs we can write:

$V_1^{CH} = \{1,2,3,4,7,8,9\}$ $V_2^{CH} = \{8,9,12,13,16,17\}$

$V_3^{CH} = \{5,6,9,10,11,14,15\}$

The optimization problem for minimizing total power consumption can be formulated as follows;

$$\begin{array}{|lll}
\text{MILP}: & & \\
& \text{Minimize } \max(E_{is}^t) & (1) \\
\textit{subject to}: & & \\
& q_i \gamma - \sum_{j \in K} t_j f_i v_j^i = 0 \quad (i \in CH) & (2) \\
& b_j \alpha_{\min} \leq t_j \leq b_j \alpha_{\max} \quad (j \in K) & (3) \\
& \sum_{j \in K} t_j c_i f_i v_j^i = E_{is}^t \quad (i \in CH) & (4) \\
& \sum_{j \in K} t_j \leq T & (5) \\
\textit{variables}: & & \\
& t_j \geq 0 \ \ (j \in K) & (6) \\
& b_j \in \{0,1\} \ \ (j \in K) & (7)
\end{array}$$

In the above formulation, objective function (1) minimizes the energy consumed by a CH that has the biggest power utilization while sending its packets to mobile sink. Since the CHs are the main power consumers in clustering algorithms, minimizing the power used by these nodes results in decreasing network total power consumption. The set of constraints in (2) to (5) can be interpreted as below. Constraint (2) states that all data buffered in i-th CH will be sent to mobile sink located at P_j, $(j:1...K)$ sites at the rate of f_i within t_j seconds. $q_i \gamma$ is the amount of buffered data in i-th CH within t_{dc} and γ is a coefficient of data fusion in all CHs. The parameter v_j^i guarantees that CHs send their data simply to the sites inside their transmission coverage and are defined as follows

$$v_j^i = \begin{cases} 1 & \text{if } P_j \in V_i^{CH} \\ 0 & \text{else} \end{cases} \qquad (6)$$

Constraint (3) lets the mobile sink to choose its set of data gathering locations from the set P_j, $(j:1...K)$. In general, for a sample location j, if the binary parameter b_j is equal to zero, the sink does not choose this point for receiving data. Thus, the sink will not stay in location j at all (t_j=0). On the other hand, if b_j is equal to 1, the mobile sink spends some time between α_{min} and α_{max} in location j and receives CHs' data at this period of time. The total power consumed by i-th CH, E_{is}^t, is formulated in (4). We assumed that the i-th CH is transmitting a portion of its data to each location p_j for t_j $(j \in K)$ seconds at the rate of f_i. The parameter v_j^i defined by (6) ensures that the i-th CH sends data simply to the locations inside its transmission range. As we described before, t_{dr} varies depending on the sensor network application. In this paper, we set this time equal to T which is showed in constraint (5). This means that the total mobile sink sojourns time in all locations must be less than T in order to avoid data expiration.

C. Evaluating CH's Transmission Range

As shown in [8], CHs' transmission range is calculated according to their residual energy and the number of remaining clustering rounds. However, here t_{dr} (maximum time for reporting data to the mobile sink) has the main role in determining CHs' transmission range. The upper and lower bounds of t_{dr} are calculated as below:

$$T_{min} \le t_{dr} \le T_{max} \tag{7}$$

$$T_{max} = \sum_{i \in CH} \theta_i \gamma \tag{8}$$

$$T_{min} = \max\{\theta_1\gamma, \theta_2\gamma, ..., \theta_{length(CH)}\gamma\} \tag{9}$$

$$\theta_i = {}^{q_i}\!/_{f_i}$$

In the case of assigning $T_{max}$for collecting data, the best data collecting place for sink is the P_j location such that $D(P_j, S_i^{ch}) < r$, where r is the minimum transmission range. It is clear that the best sink location for collecting each cluster head's data is the closest place near it. Fig. 3 demonstrates a MILP solution for our network model in the case of $t_{dr} = T_{max}$.

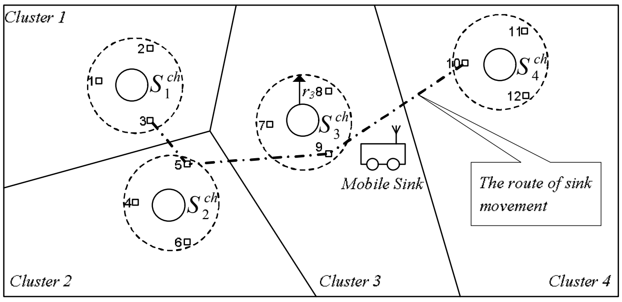

Fig. 3 One MILP solution for $t_{dr} = T_{max}$.

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On the other hand, if t_{dr} is chosen between T_{min} and T_{max} the mobile sink could not be able to collect all CHs data separately, because of insufficient time. In this case, the sink has to receive the data of two or more CHs in some locations. This needs the CHs transmission ranges to be increased until appearing some range overlapped areas. Fig. 4 represents a MILP solution for the case of $T_{min} < t_{dr} < T_{max}$.

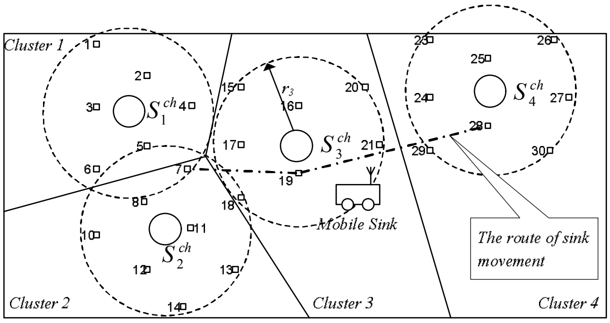

Fig. 4 One MILP solution for $T_{min} < t_{dr} < T_{max}$

Finally, in the case of selecting T_{min} for t_{dr}, it is inevitable for the mobile sink to collect CHs data from only one P_j location. Clearly, all CHs have to increase their transmission ranges until they make a point in which the mobile sink can be able to receive their data (Fig. 5). Subsequently the sink moves toward this point and receives all CHs data at the same time. The mobile sink has to stay at the point and receive data until the CH of the biggest cluster empty its buffer.

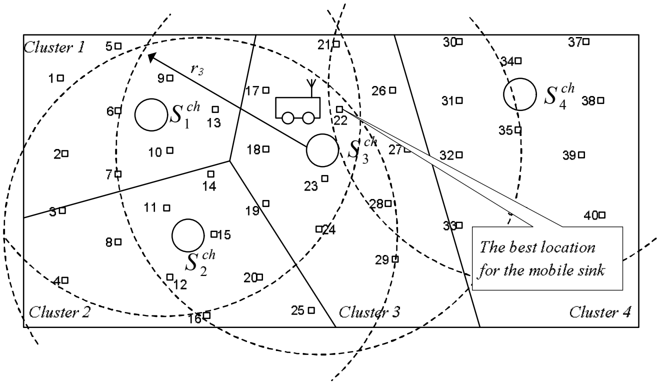

Fig. 4 One MILP solution for $t_{dr} = T_{min}$.

IV. SIMULATION RESULT:

In this section we provide simulation results of the proposed algorithm performed in MATLAB environment. The proposed scheme is compared with some similar schemes such as the one proposed in [8], in which the mobile sink moves to the optimal location in each round and [14], where the sink is fixed in the center of network in all rounds.

We initially focused on a simple scenario with a circular network area which has 100 meters radius. 100 sensors are randomly deployed all over the network, where 0.05 of them are desired to be cluster heads (ρ =.05). The radius of each cluster is initially set to 10 meters. For simplicity the CHs transmission ranges are assumed to be equal ($r_i = r$, $i = 1, ..., \rho.N$).

Other simulation assumptions are presented in Table 1.

Table1. Simulation Parameters

Parameters	*Values*
CH's bit rate	10Kbps
Energy	0.1J
Data Packet size	1000 bit
γ	0.8
θ_1	50 nJ/bit
θ_2	10 pJ/bit/m2

Table 2 represents the results of the MILP approach for t_{dr}=10s, t_{dr} =5s and t_{dr} =3s, i.e., the number of sink tarriances (P_j#), CHs' transmission range (r_j) and the minimum, maximum and average values of t_j and $D(S_i^{CH}, P_j)$. Note that t_j is the mobile sink sojourn time in location P_j and $D(S_i^{CH}, P_j)$ is the distance between *i*-th cluster head and P_j. Moreover, the maximum and total values of CHs power consumptions are given in table 2 with the notations $MAX(E_{ib}^t)$ and $SUM(E_{ib}^t)$, respectively.

As Table 2 shows, if t_{dr} is large enough, the mobile sink can come close to each CH and collect its data, which causes minimum $MAX(E_{ib}^t)$ values. By decreasing t_{dr}, CHs have to increase their transmission range in order to make two or more "range overlapped" areas. Clearly, the sets $V_i^{CH}, i = 1 \ldots \rho.N$ increase their shared members. Therefore, the mobile sink can stay between two or more overlapped areas and gather CHs' data concurrently. This leads $MAX(E_{ib}^t)$ to be increased.

In the second scenario, the proposed scheme has been compared with two other algorithms in [8] and [14], during 700 rounds. Several data reporting time spans are implemented, i.e. t_{dr}=10s, t_{dr} =7.5s and t_{dr} =5s.

As Fig. 3 shows, the proposed algorithm has better performance compared with other schemes. Both static sink and [8] lose their alive sensor nodes before 500 rounds while the proposed scheme can keep most of the nodes alive almost 650 rounds. Specially, in the case of t_{dr}=10s the proposed scheme has the best performance compared to t_{dr} =5s and t_{dr}=7.5s. That is because the mobile sink can collect CHs data from shorter distance in large t_{dr} s. This results in more energy saving at CHs, which are major energy consumer nodes in hierarchical networks. Fig. 4 represents the network's remaining energy for the mentioned schemes. The proposed scheme holds more energy compared with other algorithms, which confirms the above explanations. Static sink method [14] has the worst performance according to Fig. 4 and Fig. 5. That is because the sink is not only fixed during data collection in each round but also it does not change its location between two rounds. Consequently, CHs always have random distances from the sink which causes non-optimal energy consumption. On the other hand, the proposed scheme in [8] has better performance due to dynamically change of sink location before each round. However, [8] acts as static sink method during each round. Thus, the network lifetime is not optimized in this method since the sink is fixed while collecting data all over a round. Finally, the proposed scheme solves this problem by moving the sink even during each round ingeniously, which is maximizing network lifetime.

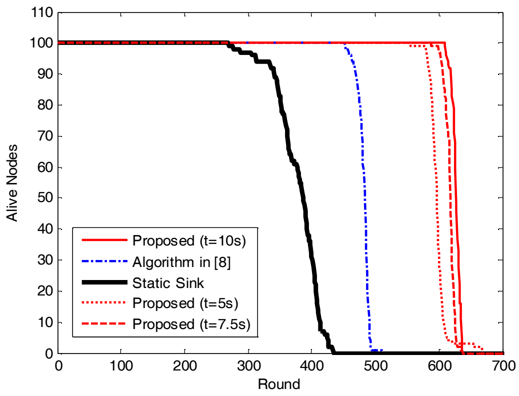

Fig4. Number of alive nodes versus round

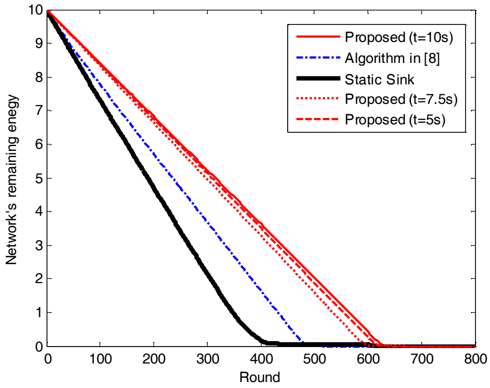

Fig 5. Total remaining energy versus round

By decreasing t_{dr}, CHs have to raise their transmission range in order to make two or more "range overlapped" areas. In this case the sink can receive data from more CHs. This leads to

Table2 -MILP simulation results for for t_{dr}=10s, t_{dr} =5s and t_{dr} =3s

t_{dr}	$CH\ \#$	$P_j\ \#$	r_i	t_j			$D(S_i^{CH}, P_j)$			SUM	SUM	MAX
				Min	Max	Avg	Min	Max	Avg	(t_j)	(E_{is}^t)	(E_{is}^t)
10s	5	5	10	1	2.88	1.64	3.23	5.83	4.63	8.2	.0041	.00144
5s	5	4	50	1	1.88	1.25	13.83	48.26	35.60	5	.0059	.00171
3s	5	2	60	1.12	1.68	1.4	39.96	58.47	49.22	3	.0060	.00209

Tabel3- The Comparison of Energy Consumption

	Proposed Algorithm			Algorithm in [8]	Static Sink
tdr	10	7.5	5		
MVEC of CHs	8.5336e-006	1.2090e-005	1.5662e-005	1.8663e-004	3.5477e-004
MEC of CHs	1.5757e-004	1.5929e-004	1.6664e-004	2.0793e-004	2.5169e-004
Network MEC	0.0159	0.0162	0.0168	0.0211	0.0262

more energy consumption in the network. For example, at t=5s the maximum transmission range is occurred. Therefore, in this case the first node dies earlier.

For a better performance evaluation of the three mentioned schemes, Table 3 shows the Mean Variance of (CHs) Energy Consumption (MVEC), Mean Energy Consumption of (CHs) (MVEC) and the network's Mean Energy Consumption (MEC) parameters in the three algorithms.

As Table 3 represents, the proposed scheme has the lowest MVEC compared with other schemes which observes the CHs energy consumption fairness. Moreover, the MEC of cluster heads and network are lower than the same parameters in other algorithms. This is because of the optimized sink mobility in proposed scheme unlike other algorithms.

V. CONCLUSION

Controlled mobility of sink in wireless sensor networks significantly increases network lifetime. In this paper, using mathematical model MILP (Mixed Integer Linear Programming), we proposed a scheme that prescribes the sink path for collecting all CHs data in t_{dr} time span while maximizing network lifetime. The mathematical model minimizes the maximum energy consumed by CHs considering several constraints, such as CHs' bounded data reporting time, CHs' buffers size, initial energy, etc. Simulation results confirm that the proposed algorithm has better performance compared with similar schemes.

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