Maximizing Common Data Rate of collection Tree in Energy-Harvesting Wireless Sensor Networks

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Abstract—Energy-harvesting wireless sensor network (EH-WSN) has the capability of capturing energy from environment and providing perpetual data services. In many applications of EH-WSN such as environmental protection, building monitoring, industrial internet of things, nodes are required to report sensed data to the sink with high common data rate to improve monitoring accuracy. In order to improve the common data rate of collection tree-based network, this paper studies collection tree construction for maximizing common data rate. We propose a collection tree construction scheme named hybridMCDRT which consists of a heuristic construction algorithm, an iterative optimization algorithm and "detour problem" elimination algorithm. The simulation results show that the proposed scheme can obtain higher common data rate than the existing methods.

1. Introduction
Wireless Sensor Network (WSN) is composed of many sensor nodes and is used to collect data. It has been widely used in many fields such as military, environment, health and smart home. In traditional WSNs, nodes generally use batteries with limited energy, and their lifetime and data rate are restricted by the energy, which brings many difficulties to the applications of WSN in the field where higher data rate is demanded. Recently, the Energy-harvesting wireless sensor network (EH-WSN) has been attracting more and more attention. In EH-WSNs, nodes are equipped with energy capture module and rechargeable battery, which can scrape energy from the environment, such as solar energy, wind energy, vibration energy and electromagnetic energy, so that sensor nodes can be free from the constraints of battery energy and significantly extend the lifetime of the nodes as well as the network. In some applications of EH-WSN(such as monitoring applications for environments, buildings), all nodes excepting the sink are required to report sensory data to the sink at a common data rate [1]. In this paper, we call the maximum data rate that all nodes in the network can jointly support as common data rate (CDR). Raising the CDR can help improve the monitoring accuracy. Therefore, maximizing the CDR is one of the goals pursued by many EH-WSN applications.

The collection tree routing is widely used in EH-WSNs, since it has some advantages such as simple calculation and no routing table, which is suitable for the weak computing capacity and small storage space of sensor nodes. To the best of our knowledge, there are few literatures devoted to the issue of maximizing the CDR of collection tree-based EH-WSNs. In this paper, we study collection tree construction scheme aim to maximizing CDR of EH-WSN.

The main contributions of this paper are as follows: (1) a collection tree construction scheme named hybridMCDRT is proposed to construct a collection tree with the maximum CDR. The hybridMCDRT consists of three components: 1) iMNL-based MCDRT, a heuristic construction algorithm to construct a collection tree with optimal CDR; 2) MITT-based MCDRT, an iterative optimiza-
tion algorithm which optimizes the collection tree iteratively; 3) a collection tree adjustment algorithm to eliminate the "route bypass" problem existing in the collection tree. (2) The proposed algorithms are verified by extensive experimental simulations.

2. Related works

A lot of efforts have been done on maximizing the CDR of EH-WSNs. Literatures [2-4] studied the problem on maximizing the CDR of EH-WSNs in the scenarios where mobile sink nodes are used. Among them, Literature [2] proposed a method for maximizing the CDR based on slot scheduling optimization in application scenarios where the sink node performs data collection in a single-hop manner. Literature [3] proposed to use a mobile sink to improve the CDR of EH-WSN where the sink mobiles in a certain area. Literature [4] put forward a CDR maximization method based on optimization of transmission rate and transmission time slot scheduling of nodes. However, the research results of the above literatures are not suitable for the scenarios where the sink is stationary. Literatures [1, 5-7] studied the CDR maximization of EH-WSN through route optimization. Literature [1] proposed a linear programming-based optimization to maximize the CDR. Literature [5] put forward a CDR maximization scheme for EH-WSNs where nodes have data aggregation capabilities. Literature [6] studied the problem of maximizing the CDR of energy-cooperative EH-WSNs, and proposed a distributed iterative algorithm for maximizing the CDR based on cooperation of energy routing and data routing. Literature [7] modelled the EH-WSN throughput maximization problem as a convex optimization problem to obtain a global optimal solution, and further improved network throughput through energy cooperation.

Collection tree routing has the advantages of simple calculation, no need of routing tables, et al, it can adapt to the weak computational capability and low storage space of sensor nodes [8], and it is widely used in EH-WSNs. However, literatures [1, 5-7] mainly studied the problem of maximizing the CDR under the non-tree data collecting strategy in EH-WSNs. Therefore, the research results cannot be directly applied to the problem of maximizing the CDR of collection tree-based EH-WSNs.

To the best of our knowledge, there is few literature devoted to the CDR maximization of collection tree-based EH-WSNs. Literature [1] studied the CDR maximization problem given a certain collection tree, and proposed a distributed algorithm named DLEX to maximize the CDR. However, given a network deployment, many different data collection trees can be constructed. According to the characteristics of tree, nodes have different numbers of descendant nodes in different collection trees. In the case where the node capture energy is determined, the more descendants of a node, the less data it can forward for each descendant node, that is, the smaller CDR it can support. Obviously, different collection trees result in different CDRs. Therefore, constructing an optimal data collection tree according to the captured energy of nodes in EH-WSN is an effective way to improve the CDR. However, there are few studies done on this topic. Literature [9] proposed a parent node switching method based on the Markov decision process to balance the energy consumption of nodes so as to maintain the energy sustainability of the collection tree. However, the optimization goal is not to maximize the CDR.

When the captured energy of nodes during a certain period is highly predictable, the problem of maximizing the CDR of EH-WSNs is similar to the problem of maximizing the network lifetime of the traditional WSNs with certain data collection rate. Many literatures define the lifetime of WSN as the lifetime of the first failed node [10]. A lot of efforts have been done on maximizing the lifetime of WSNs based on collection tree optimization. Literatures [11-14] studied maximizing the lifetime of tree-based WSNs with nodes having data aggregation capabilities. Literature [11] proved that constructing a collection tree with the maximum network lifetime is an NP-hard problem, and an algorithm was proposed to optimize the network lifetime by iteratively reducing the energy load of the bottleneck nodes from an arbitrary collection tree. Literatures [12, 13] studied the problem of constructing the shortest-path collection tree with the largest network lifetime, and proposed a method for selecting the maximum lifetime tree from the shortest path trees. Literature [14] studied constructing collection tree with the maximum network lifetime under delay constraint in the unreliable WSNs, and proposed
a collection tree construction method based on energy and delay perception. Literature [15] proposed a method based on the combination of minimum energy spanning tree and information ferrying to extend the network lifetime. Literature [16] proved that constructing the maximum network lifetime collection tree in WSNs where nodes have no data aggregation capabilities is an NP-hard problem and a heuristic collection tree construction method MNL was proposed. The literature [17] models the maximum network lifetime collection tree construction as the minimum-maximum weight spanning tree problem, and proposed an iterative algorithm named MITT for building a maximum network lifetime collection tree. MITT starts from an arbitrary collection tree and iteratively associates the descendant nodes of bottlenecks to neighbor nodes with a smaller energy load to continuously optimize the network lifetime. The experimental results show that the MITT algorithm is superior to the heuristic construction algorithm such as PEDAP-PA [18], MNL. Literature [19] proposed a maximum network lifetime collection tree construction algorithm named RaSMaLai, which also uses iterative adjustment strategy to continuously optimize the network lifetime, but its adaptability to the size and topology of networks is not as good as MITT. Literature [20] models the maximum network lifetime collection tree construction as a mix integer linear programming problem (MIP), and converts the MIP problem to linear programming problem by converting each nonlinear equation in the MPI problem into a set of linear equations. Literature [21] proposed an exact algorithm for constructing the maximum network lifetime collection tree using integer linear programming. However, the methods proposed in literatures [20, 21] are only suitable for small-scale networks.

3. hybridMCDRT

3.1. Network model and problem description

This paper makes the following assumptions about the EH-WSNs to be studied: once the sensor nodes are deployed, their positions will not change; the sink node has sufficient energy, other nodes capture energy from the environment, and is equipped with a large-capacity rechargeable battery; the captured energy of nodes during a certain period are highly predictable; there is at least one path between each sensor node and the sink node, i.e. there is no isolated node in the network.

We represent a EH-WSN as an undirected graph \(G(V, A)\), where \(V\) is the set of nodes, including the sink node (indicated by \(s_0\)), \(A\) is the link set. \(d_0\) represents the communication radius of nodes, \(<u, v>\) and \(d(u, v)\) represent the communication links and distances between the nodes \(u, v\), respectively. Thus, \(A=\{<u, v>|d(u, v)\leq d_0, u, v \in V\}\). In addition, \(N(u)\) represents the one-hop neighbors of node \(u\), \(T(V_T, A_T)\) represents a spanning tree rooted at \(s_0\) in graph \(G(V, A)\), and \(V_T\) represents the set of nodes in the spanning tree \(T\). \(A_T\) represents the set of links in the spanning tree \(T\). The \(p_v\) represents the parent node of node \(v\). \(TL(v)\) indicates the tree level of node \(v\), which is equals to the tree level of \(p_v\), plus 1, and \(TL(s_0)=0\). Additionally, \(D_N\) and \(A_N\) represent the descendant nodes and ancestor nodes of node \(v\), respectively, and \(n_v\) represents the number of nodes in \(D_N\).

During period \(t\), the captured energy of node \(v\) is denoted by \(E_v^h(t)\), and the amount collected data is denoted by \(\sigma(v \in V)\). \(e_1\) and \(e_0\) represent energy consumption for sending and receiving one bit, respectively. The amount of data received by node \(v\) from the descendant nodes is \(\sigma n_v e_0\), and the energy consumption for receiving is \(\sigma n_v e_0\). The node \(v\) sends its own data and the data from its descendant nodes to the parent node. The total energy consumption is \(\sigma(n_v e_0 + n_v e_1 + e_1)\). The energy consumed by node \(v\) for forwarding data cannot exceed its captured energy, that is, \(\sigma(n_v e_0 + n_v e_1 + e_1) \leq E_v^h(t)\).

\[
\sigma \leq \sigma_v^* = \frac{E_v^h(t)}{(n_v e_0 + n_v e_1 + e_1)}
\]  

(1)

\(\sigma_v^*\) represents the maximum amount of data that node \(v\) can transmit for itself and each descendant node according to the captured energy during period \(t\). Therefore, when using the tree \(T\) to collect data, the CDR can be expressed as

\[
CDR(T) = \frac{\min_{v \in T} \{\sigma_v^*\}}{t}
\]  

(2)
Given a network deployment, many different collection trees can be generated, and different collection trees have different CDRs. We refer to the collection tree with the maximum CDR as the maximum common data rate tree (MCDRT). From [16], it can be seen that finding the MCDRT is an NP-hard problem. Learning from the ideas of the WSN maximum network lifetime collection tree construction algorithms, the MCDRT construction algorithms can also be divided into the following two categories: heuristic construction algorithms and iterative adjustment optimization algorithms. Experiments show that the iterative adjustment optimization algorithms are superior to the heuristic construction algorithms, but the initial collection tree has a great influence on the performance of the iterative adjustment optimization algorithms.

In this paper, a MCDRT construction scheme named hybridMCDRT which uses both heuristic construction strategy and iterative adjustment optimization strategy is proposed. The basic strategy of the hybridMCDRT is as follows: First, a heuristic algorithm named iMNL-based MCDRT is used to construct a MCDRT; then the iterative adjustment algorithm named MITT-based MCDRT is used to continuously optimize the collection tree; finally, a collection tree adjustment algorithm is used to eliminate the "route bypass" problem existing in the collection tree.

3.2. iMNL-based MCDRT

Through learning and improving the idea of MNL[16], an MCDRT heuristic construction algorithm named iMNL-based MCDRT is proposed. The basic idea is as follows: Starting from the sink node \( s_0 \), other nodes join the collection tree one by another according to the following policy: each time the node which results in the maximum CDR is added to the collection tree until all nodes in the network join the collection tree. In this process, when there are multiple nodes that result in the same maximum CDR, the node having more captured energy is preferentially selected to join the collection tree. The detail of the iMNL-based MCDRT algorithm is as follows:

\[
\text{Algorithm A iMNL-based MCDRT (G)}
\]

\[
V_T = \{s_0\}, \quad A_T = \emptyset, \quad V_L = V - \{s_0\}, \quad TL(s_0) = 0
\]

\[
\text{WHILE } V_L \neq \emptyset \text{ DO}
\]

\[
\text{maxR} = 0
\]

\[
\text{FOREACH } u \in V_L \text{ DO}
\]

\[
\text{FOREACH } v \in V_T \text{ DO}
\]

\[
\text{IF } <u, v> \in A \text{ THEN}
\]

\[
T_{\text{tmp}} = (V_T \cup \{u\}, A_T \cup \{<u, v>\})
\]

\[
\text{IF } \text{CDR}(T_{\text{tmp}}) = \text{maxR} \text{ THEN}
\]

\[
\text{maxR} = \text{CDR}(T_{\text{tmp}}), \quad <u^*, v^*> = <u, v>
\]

\[
\text{ELSEIF } \text{CDR}(T_{\text{tmp}}) = \text{maxR}
\]

\[
\text{AND } E^u(t) > E^v(t) \text{ THEN}
\]

\[
<u', v^*> = <u, v>
\]

\[
\text{ENDIF}
\]

\[
\text{ENDIF}
\]

\[
\text{ENDFOR}
\]

\[
\text{ENDFOR}
\]

\[
V_T = V_T \cup \{u^*\}, \quad A_T = A_T \cup \{<u^*, v^*>\}
\]

\[
V_L = V_L - \{u^*\}, \quad TL(u^*) = TL(v^*) + 1
\]

\[
\text{ENDWHILE}
\]

\[
\text{RETURN } T(V_T, A_T)
\]

3.3. MITT-based MCDRT

After a MCDRT is constructed by the iMNL-based MCDRT algorithm, the hybridMCDRT needs to use an iterative adjustment algorithm to optimize the collection tree. Literature [17] models the maximum network lifetime collection tree construction in WSNs as a minimum-maximum weight spanning tree problem, and proposed the MITT algorithm that optimizes the network lifetime by iteratively adjusting the collection tree. In MITT, starting from an arbitrary collection tree, the descendant nodes of the largest weight node are iteratively associated with neighbor nodes with smaller weights to continuously reduce the weight of the collection tree, thereby continuously optimizing the network lifetime. In
EH-WSN, when the captured energy of nodes during a certain period are highly predictable, the problem of maximizing the CDR of EH-WSN is similar to the problem of maximizing the network lifetime of traditional WSN with all nodes having a common data rate. Therefore, leaning from the idea of MITT, we propose an MITT-based MCDRT to improve the collection tree for maximizing the CDR. The thinking of the MITT-based MCDRT algorithm is similar to that of the MITT algorithm. The main difference is that the MITT-based MCDRT algorithm gives different meaning to the node weight and the collection tree weight. The definitions of node weight and collection tree weight used in the MITT-based MCDRT algorithm are given below.

**Definition 1 Node weight**: The weight of node $v$ ($v \in V_T\setminus \{s_0\}$) in a collection tree $T$ is defined as

$$w(T, v) = \frac{1}{\sigma^v} = \frac{n_v e_0 + n_v e_1 + e_3}{E^v_B(t)}.$$  \hspace{1cm} (3)

The node weight represents the ratio of the total energy consumed by node $v$ to forward 1 bit for each node in its sub-tree to its captured energy. The larger the ratio, the less data it can forward for each sub-tree node.

**Definition 2 Collection tree weight**: The weight of a collection tree $T$ is defined as

$$w(T) = \max_{v \in V_T\setminus \{s_0\}} w(T, v).$$  \hspace{1cm} (4)

The greater the collection tree weight, the smaller the CDR. In order to increase the CDR based on a collection tree $T$, it is necessary to continuously reduce the collection tree weight $w(T)$, that is, the weight of the bottleneck node in the collection tree. The overall strategy of the MITT-based MCDRT algorithm, similar to the MITT algorithm, is to iteratively associate the descendant nodes of the bottleneck node to other sub-tree nodes with smaller weights, thus gradually reducing the collection tree weight. Therefore, the MITT-based MCDRT algorithm can be obtained simply by replacing the node weight and the collection tree weight in the MITT algorithm with the equations (3) and (4), respectively. For the MITT algorithm, please refer to [17], which is not repeated here.

### 3.4. Collection tree adjustment

Through experiments, we found "route bypass" problem existing in the collection tree optimized by the MITT-based MCDRT algorithm, an example of which is shown in Fig. 1, where solid lines with arrow indicate collection tree route and dotted lines indicate the links existing between the nodes. For example, the path that node $F$ transmits data to the sink based on the collection tree route is $F \rightarrow A \rightarrow B \rightarrow \text{sink}$, but in fact, node $B$ is not only an ancestor but also a one-hop neighbor of node $F$, so the data of node $F$ is not necessary to bypass node $A$, it can flow to the sink through node $B$. Node $E$ also has a similar problem.

![Fig. 1. An example of "route bypass" problem](image)

The "route bypass" problem not only wastes energy, but also increases the number of transmission hops, thereby increasing the end-to-end delay. In order to solve the "route bypass" problem, we propose a collection tree adjustment algorithm $\text{RegulateRoutingTree}$ to eliminate route bypass, the steps are as follows.

**Algorithm B $\text{RegulateRoutingTree}(T)$**

FOREACH $v$ IN $V_T\setminus \{s_0\}$ DO

1. $u = \arg \min_{w \in \text{parents}(v) \cap \text{ancestors}(v)} \text{TL}(w)$
2. IF $u \neq p_v$ THEN
   1. $p_v = u,$ $\text{TL}(v) = \text{TL}(u) + 1$
   2. updateTreeLevelInSubTree($v$)

ENDIF
The function `updateTreeLevelinSubTree(v)` is used to update the tree layer of all descendant nodes of node `v`, the code is as follows:

```plaintext
FUNCTION updateTreeLevelinSubTree(v)
    FOREACH x IN {x | p_x = v, x ∈ N(v)} DO
        TL(x) = TL(v) + 1
        updateTreeLevelinSubTree(x)
    ENDFOR
ENDFUNCTION
```

Obviously, the collection tree adjustment algorithm `RegulateRoutingTree` does not cut down the CDR of the collection tree. Fig. 2 shows the collection tree obtained by adjusting the collection tree shown in Fig. 1 using Algorithm B.

![Fig. 2. An example of eliminating route bypass](image)

3.5. Implementation scheme

When an EH-WSN is deployed, an initial collection tree is constructed by a distributed collection tree construction method such as that proposed in [22]. After joining the collection tree, each node collects the information of its one-hop neighbors and predicts the energy will be captured in the upcoming `t`-time period, and sends the information to the sink through the initial collection tree route. Based on the adjacency information of nodes and the predicted energy, the sink constructs a collection tree by using the hybridMCDRT, and calculates the CDR of the collection tree. Then, the topology information of the collection tree and the CDR are sent to each node. After receiving the topology information and the CDR, nodes perform data collection task at the CDR, and forward their data based on the collection tree route. After `t` time, the sink reconstructs the collection tree based on the predicted energy of nodes, and calculates the CDR of the newly obtained collection tree again. It is not difficult to find that the communication energy consumption in the collection tree reconstruction process is almost equal to the communication energy consumption of collecting two data packages from each node.

4. Experiment simulation and result analysis

In order to verify the algorithms proposed in this paper, a variety of network settings with different node density and different number of nodes are simulated (node density is defined as the number of nodes in an area of $\pi d^2$). For each network setting, randomly generate 200 network topologies (the results shown below are from the average of 200 network topologies), and the location of the sink are selected randomly. For each network topology, the following five types of MCDRT construction algorithms are implemented: MNL-based MCDRT algorithm (It draws on the idea of the MNL algorithm, referred to as MNL for short), iMNl-based MCDRT algorithm (It draws on and improves the idea of the MNL algorithm, abbreviated as iMNl), the MITT-based MCDRT algorithm (It draws on the idea of the MITT algorithm, abbreviated as MITT), the MITT-based MCDRT with MNL algorithm (It combines MNL and MITT, referred to as hybrid MCDRT1 for short), and the MITT-based MCDRT with iMNl (it combines iMNl and MITT algorithm, abbreviated as hybrid MCDRT2). The relevant parameters used in simulations are shown in Table 1.

| Table 1 The parameters setting of simulations |
|-----------------------------------------------|
| parameters             | values               |
| $e_0$                  | 50 nJ/bit$^{[18]}$   |
| $e_1$                  | 100 nJ/bit$^{[18]}$  |
First, the CDRs obtained by the iMNL algorithm and the MNL algorithm are compared and the results are shown in Fig. 3. From Fig. 3, it is easy to find that the iMNL algorithm is superior to the MNL algorithm, and its performance increases with the increase of network size and node density. This is because with the increase of network size and node density, there may be multiple candidate nodes which result in the same CDR during the growth of the collection tree. Different from MNL, iMNL always selects the node with most energy from multiple candidate nodes to join the collection tree, so that the newly-acquired collection tree has more energy, thereby increasing the possibility that the subsequently generated collection tree have a larger CDR.

Then, the performance of hybrid MCDRT1 algorithm, hybrid MCDRT2 algorithm, and MITT algorithm are compared. The comparison results are shown in Fig. 4. It shows that the hybrid MCDRT1 algorithm and the hybrid MCDRT2 algorithm are better than the MITT algorithm, and the hybrid MCDRT2 algorithm is better than the hybrid MCDRT1 algorithm. The experimental result shows that the quality of the initial collection tree is important to the performance of the MITT algorithm, which also validated the effectiveness of the hybridMCDRT.

5. Conclusions
This paper studies the problem of constructing collection tree in EH-WSNs for maximizing CDR, proposes the hybridMCDRT which consists of a heuristic construction algorithm, an iterative optimiza-
tion algorithm and "detour problem" elimination algorithm to construct MCDRT in EH-WSNs. The hybridMCDRT can be used not only to solve the problem of maximizing the CDR for EH-WSNs but also to address the problem of maximizing the network lifetime for WSNs where all nodes work at a common data rate.

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