Research of an Adaptive Aggregation Routing Algorithm in Wireless Sensor Networks

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Abstract—At present, most aggregation routing algorithms for WSNs assume that aggregation expend is so little as to be neglected. But with the growing demand for the collection of multimedia data, the aggregation expend are much larger and can’t be neglect. In view of this problem, this paper proposes an adaptive aggregation routing algorithm with the minimal energy consumption (RMEAAT). Firstly, it constructs an $\alpha$-balancing spanning tree on the basis of SPT and MST as the initial communication path. And then it defines the aggregation benefit with consideration of aggregation expend and transmission expend, and data are adaptively judged whether to aggregate at every node of $\alpha$-balancing spanning tree according to aggregation benefit in the process of transmission. Correspondingly, the initial transmission path is gradually improved in terms of the aggregation judgment. The simulation results show that RMEAAT algorithm has better performance in WSN with different aggregation expend and fusion degree.

Index Terms—wireless sensor network, data aggregation, fusion degree, routing

I. INTRODUCTION

A wireless sensor network (WSN) is composed of a large of number of tiny sensor nodes with very limited resource. Especially, the battery power of nodes is very rare and can’t be replenished. So how to save energy is a primary problem for the design of WSNs. If the monitoring data of each node are independently transferred to sink without any fusion processing, plenty of energy and communication bandwidth will be wasted. So it is very necessary to aggregate data during the transmission process, so as to reduce the amount of data and save energy. Recently many scholars have done plenty of research in this area. Some aggregation routing algorithms, such as GIT, PEGASIS, and TEEN, are proposed. The experimental results show that these algorithms can greatly save energy and prolong the lifetime of network. But they neglect the aggregation expend, and data are fused at every intersection.

With the development of WSNs, more and more multimedia data needs to be collected, such as voice, image or video. It is a more complicated calculation process to aggregate the multimedia data in WSNs. Ref.[5] has experiments on the aggregation overhead of acoustical signal, and the results indicate that the overhead is more than 10nJ/bit. Luohong analyzes the fusion expend of image data, and the results also demonstrate that the expend is about 75nJ/bit. In WSNs, the receiving overhead of data is about 50nJ/bit. It’s evident that the aggregation overhead is about the same as the receiving overhead. Therefore, even the overhead of the simplest convergence process can’t be neglected in multimedia WSNs.

Because of the convergence overhead, it is no longer an optimal method that data are integrated at all intersections. Especially, if the fusion degree is smaller and the aggregation expend is larger, the saved communication overhead result from aggregation maybe can’t compensate the aggregation expend. That is, data convergence is not only unnecessary, but also increases the network’s energy consumption. As a result, whether to aggregate at a node should be adaptively decided by aggregation expend and the saved transmission overhead. It is an NP-hard problem to solve the optimal convergence routing with the minimal total energy consumption, and currently few people study the issue. Bhong proposes a DAGP algorithm which discusses convergence and communication expend. But this algorithm isn’t suitable for the sensor networks which need periodic data collection. Luohong presents an adaptive fusion algorithm AFST with consideration of communication and fusion expend. However in this algorithm, the topological structure of transmission is on the basis of binary tree, which seriously increases the times of forwarding and transmission distance, and holds back the further optimization of the network performance.

Due to above shortcomings, this paper proposes a routing algorithm based on the minimal energy adaptive aggregation tree (RMEAAT). The remainder of this paper is organized as follows. Section 2 defines the optimal aggregation routing model with consideration of communication and convergence expend. Section 3 describes the construction process of $\alpha$-balance spanning tree ($\alpha$-BST) as the initial transmission path on the basis of the minimal spanning tree (MST) and the shortest path tree (SPT). Section 4 gives the definition of aggregation benefit and the judgment method of adaptive aggregation in the process of data transmission along $\alpha$-BST. On the basis of the adaptive aggregation judgment, our algorithm RMEAAT is proposed in section...
can be proved as follows: According to the free spatial model [4], is given and \( \alpha \) falls in between \( \omega \) is amended as \( \omega - \) times than the weight of every \( \omega \) denotes all \( \omega \) - \( \omega \) times than the weight ),(\( \omega \) - \( \omega \) denotes the weight of edge ),(\( \omega \) in ; \( \omega \), the path length of every node to sink \( \omega \) - \( \omega \) times than its shortest path length in \( \omega \) denotes the amount of data after aggregation at \( \omega \) and all source nodes, and edge set \( \omega \) - \( \omega \) denotes the value of )\((\alpha \omega \) - \( \omega \) to sink. Initially, the value of \( \omega \) is equal to \( \infty \) for every non-root node, equal to 0 for root node \( \omega \) .

(d) Traverse every node \( \omega \) of \( \omega \), and judge whether the value of \( \omega \) is more \( \alpha \) times than the sum of weight from \( \omega \) to sink in \( \omega \). If true, the shortest path from \( \omega \) to sink in \( \omega \) is added to the current \( \omega \) structure, and the value of \( \omega \) is modified . Otherwise, the path of \( \omega \) in \( \omega \) keeps unchanged.

(e) In the subsequent traversal, if the value of \( \omega \) becomes smaller, and when the neighbor node \( \omega \) of \( \omega \) is visited, the value of \( \omega \) and the transmission path of \( \omega \) are adjusted as follows:

If \( \omega \) is true, \( \omega \) is modified as \( \omega \) - \( \omega \) to \( \omega \) is amended as \( \omega \) - \( \omega \) times than the value of \( \omega \) and \( \omega \) remains the same.

In \( \alpha - \omega \), the path length of every node to sink isn’t more \( \alpha \) times than its shortest path length in \( \omega \), and the weight sum of all edges doesn’t exceed \( 1 + \frac{2}{\alpha - 1} \) times of \( \omega \). It can be clearly seen that the performance of \( \alpha - \omega \) falls in between \( \omega \) and \( \omega \). Therefore, it can well adapt to WSNs with different fusion degrees. The performance of \( \alpha - \omega \) can be proved as follows:

Theorem 1 In \( \alpha - \omega \), the weight of every node \( \omega \) to sink is no more \( \alpha \) times than that in \( \omega \).

Proof: In the traversal of \( \omega \), when node \( \omega \) is
visited, and if the value of \( d(v) \) is more \( \alpha \) times than that in \( SPT \), the shortest path of \( v \) is added to \( MST \). Accordingly, the weight \( d(v) \) is equal to \( SP(v, S) \), where \( SP(v, S) \) denotes the weight from \( v \) to Sink in \( SPT \). So after node \( v \) is visited, the weight from \( v \) to sink will never exceed \( \alpha \times SP(v, S) \). That is, the conclusion is correct.

**Theorem 2** In \( \alpha - BST \), the weight sum of all edges is no more \( (1 + \frac{2}{\alpha - 1}) \) times than that of \( MST \).

**Proof:** Suppose root node ( or sink ) of \( \alpha - BST \) to be marked as \( v_0 \). In the traversal of \( MST \), all nodes are divided into two kinds: one is those nodes which are added to the shortest paths, the other is the remainder nodes. Assume \( K \) nodes are added the shortest paths, noted for \( v_1, v_2, \ldots, v_K \). If the shortest path of node \( v_{i-1} (1 \leq i \leq K) \) in \( SPT \) has been added to \( MST \), the influence on \( d(v_i) \) is as follows.

According to the construction rule of \( \alpha - BST \), if
\[
d(v_i) \leq SP(v_{i-1}, S) + MS(v_{i-1}, v_i),
\]
d(\( v_i \)) keep the same, where \( MS(v_{i-1}, v_i) \) denotes the weight from \( v_i \) to \( v_{i-1} \) in \( MST \). Otherwise, if
\[
d(v_i) > SP(v_{i-1}, S) + MS(v_{i-1}, v_i),
\]
d(\( v_i \)) should be modified as
\[
d(v_i) = SP(v_{i-1}, S) + MS(v_{i-1}, v_i).
\]
So after the shortest path of \( v_{i-1} \) is added, \( d(v_i) \) is sure to satisfy
\[
d(v_i) \leq SP(v_{i-1}, S) + MS(v_{i-1}, v_i). \tag{1}
\]
In addition, after node \( v_i \) is visited, its shortest path is also added to current \( MST \). So \( d(v_i) \) is sure to meet
\[
d(v_i) > \alpha SP(v_i, S) \tag{2}
\]
From (1) and (2), it is known that
\[
\alpha SP(v_i, S) < SP(v_{i-1}, S) + MS(v_{i-1}, v_i)
\]
Accumulating above formula from 1 to \( K \), we can get
\[
\alpha \sum_{i=1}^{K} SP(v_i, S) < \sum_{i=1}^{K} [SP(v_{i-1}, S) + MS(v_{i-1}, v_i)]
\]
After transposition,
\[
(\alpha - 1) \sum_{i=1}^{K} SP(v_i, S) \leq \sum_{i=1}^{K} MS(v_{i-1}, v_i) \tag{3}
\]
Because every edge is visited twice in the depth-first search of \( MST \),
\[
\sum_{i=1}^{K} MS(v_{i-1}, v_i) \leq 2\alpha(MST) \tag{4}
\]
From (3) and (4), the following relationship
\[
\sum_{i=1}^{K} MS(v_{i-1}, v_i) \leq 2\alpha(MST)
\]
is true, which represents the weight sum of all shortest paths added to \( MST \) is no more \( \frac{2}{\alpha - 1} \) times than the weight of \( MST \). Therefore, the final weight sum of \( \alpha - BST \) satisfies
\[
\omega(BST) \leq (1 + \frac{2}{\alpha - 1})\omega(MST).
\]
That is, the Theorem 2 is correct.

If let \( \beta = 1 + \frac{2}{\alpha - 1} \), \( \alpha \) and \( \beta \) respectively denote the similar degrees of performance between \( \alpha - BST \) and \( SPT \), \( \alpha - BST \) and \( MST \). We use \( \gamma = \alpha + \beta \) to measure the performance of \( \alpha - BST \). When the value of \( \gamma \) is minimal, the performance of \( \alpha - BST \) is optimal. Through simple calculation, when \( \gamma = (1 + \sqrt{2}) \), \( \gamma \) reach the minimal. So in RMEAAT algorithm, the initial transmission path is the \( \alpha - BST \) where \( \alpha \) is equal to \( (1 + \sqrt{2}) \).

IV. AGGREGATION BENEFIT AND ADAPTIVE AGGREGATION JUDGEMENT

In order to realize the optimal adaptive aggregation with the minimal energy expends, we must weigh the relationship between aggregation expend and saved transmission expend for intermediate nodes so as to judge whether to aggregate. The definition of aggregation benefit is given as follows:

**Definition 2** In WSNs, the aggregation benefit of edge \( e = (u, v) \), marked as \( \Delta(u, v) \), is the difference in value between aggregation expend \( E_A \) on the edge \( e \) and the saved transmission expends \( AE_T \) due to aggregation. In brief, \( \Delta(u, v) \) denotes the saved energy for network system owing to aggregation on edge \( e = (u, v) \).

The reduced data quantity after convergence is determined by data correlation between \( u \) and \( v \). Using the spatial data correlation model, the correlation coefficient \( \rho_{uv} \) is expressed as the following:
1. \( \rho_{uv} = 0 \), when \( d > r_C \),
(b) $\rho_{uv} = 1 - \frac{d}{r_c}$, when $d \leq r_c$.

Where $d$ and $r_c$ respectively denote the distance and the relevant range between two nodes; the value of $r_c$ is equal to twice of the node's sensing range.

The amount of data $\tilde{m}(v)$ after convergence can be expressed as (5)\(^6\):

$$\tilde{m}(v) = \max(m_0(u), m_0(v)) + \min(m_0(u), m_0(v))(1 - \rho_{uv})$$

Therefore, the aggregation benefit $\Delta(u, v)$ can be calculated through (6):

$$\Delta(u, v) = \Delta E_T - \Delta E_d = [(m_0(u) + m_0(v)) - \tilde{m}(v)]$$

$$T(v, S) - [(m_0(u) + m_0(v))q(e)]$$

where $T(v, S)$ indicates the transmission expend of unit data from $v$ to sink along the aggregation tree.

In the adaptive aggregation routing, if node $v$ has only one subnode $u$, $\Delta(u, v)$ can be calculated through (6). Otherwise, if node $v$ has $K$ ($K \geq 2$) subnodes $u_1, u_2, \ldots, u_K$, the aggregation benefit $\Delta(u_1, u_2, \ldots, u_K, v)$ can be gradually computed at node $v$ as the following.

According to the correlation coefficient $\rho_{u_1v}$ and (5), $\tilde{m}(v, u_1)$ and $\Delta(u_1, v)$ can be got; let $m_0(v) = \tilde{m}(v, u_1)$, and $\tilde{m}(v, u_2)$ and $\Delta(u_2, v)$ can be also computed through (5) and (6) after the data reach $v$ from $u_2$; by the same way, $\Delta(u_1, u_2, \ldots, u_K, v)$ can be solved after all subnodes $u_1, u_2, \ldots, u_K$ arrive at node $v$.

From the definition of aggregation benefit $\Delta(u, v)$, it is known that data aggregation at $v$ can lower the energy expend if $\Delta(u, v) > 0$; otherwise, aggregation maybe brings about more energy consumption. So in the optimal adaptive aggregation routing, if $\Delta(u, v) > 0$, data aggregation at $v$ is feasible; otherwise, data are directly forwarded to the next node without aggregation.

V. DESCRIPTION OF RMEAAT ALGORITHM

**Theorem 3** In the adaptive aggregation routing with $\alpha$-BST as the basic transmission path, if the data of subnode $u$ needn’t be aggregated at node $v$, the data are never aggregated anymore in the future transmission path.

**Proof:** In $\alpha$-BST, assuming $u$ to be a subnode of $v$, and the data of $u$ are transferred to sink along the path $u \rightarrow v \rightarrow w \rightarrow \ldots \rightarrow v^n$ if the data of $u$ needn’t be aggregated at node $v$ through judgment, the aggregation benefit $\Delta(u, v) < 0$. In addition, $u$ transfers the data along the path of MST. From the feature of MST, it’s known that node $u$ is the nearest to node $v$ than to any other nodes. That is, $d(u, w) \geq d(u, v)$. The definition of the correlation coefficient $\rho$ indicates that $\rho$ is in inverse proportion to the distance between nodes, so $\rho_{uw} \leq \rho_{uv}$. Furthermore, aggregation benefit $\Delta$ is in direct proportion to $\rho$, so $\Delta(u, w) \leq \Delta(u, v) < 0$. In other words, the data of $u$ needn’t be aggregated at $w$. That is, theorem 3 is correct.

From above proof, it can be seen that if the data of $u$ needn’t be aggregated at node $v$, it can be directly transmitted along the shortest path of SPT instead of along the given path in $\alpha$-BST so as to reduce transmission expend. Therefore, the RMEAAT algorithm based on $\alpha$-BST is as follows:

(a) Let $\alpha = 1 + \sqrt{2}$, and construct $\alpha$-BST as the initial transmission path of WSN.

(b) In $\alpha$-BST, suppose the identification $\theta(v)$ to represent whether some a node $v$ transfers data to sink along its shortest path. If true, $\theta(v) = 0$; otherwise, $\theta(v) = 1$.

(c) If $\theta(v) = 0$, data are adaptively judged whether to aggregate at node $v$ before transmission, which is decided by formula(6); and then $v$ forwards the data along the shortest path.

(d) If $\theta(v) = 1$, data are also adaptively judged whether to aggregate at node $v$ before transmission. If aggregation benefit is more than 0, the integrated data are transferred along the shortest path of $v$ without consideration of aggregation in the subsequent transmission.

V. SIMULATION AND ANALYSIS

The performance of RMEAAT is analyzed through the following two sets of experiments in Omnet++ simulation environment.

(a) Compare the total energy expends of RMEAAT with that of MST, SPT and BST under certain conditions, such as the particular fusion degree(0 or 1).

(b) Compare the total energy expend of RMEAAT with that of GIT, DAGP and AFST when the aggregation expend of unit data $q_0$ is assumed to be three circumstances(severe expend, moderate expend and mild expend).

Assuming 100 sensor nodes are randomly distributed in 100m×100m square area. There is only one sink in WSN. The length of the collected packet is 2000bit in a monitoring cycle. The initial energy of every sensor node is 1.5J. Data transmission bases on
the free-space RF model.

For the first set of experiment, assume the range of the maximal communication radius R to be [5m,40m]. When \( r_c = 0.1 \text{m} \), the fusion degree of WSN approaches 0. When \( r_c = 1000 \text{m} \), the fusion degree of WSN approaches 1. The performace of the routing algorithms is compared in the following two kinds of situations.

![Figure 1](image1.png)

- The aggregation expend of unit data \( q_0 \) is zero.

Fig.1(a)–(b) show the energy expend of BST is always between that of SPT and MST, which further verifies the correctness of theorem1 and theorem2. That is, BST has better performance in any extreme cases. When the fusion degree is close to 0, the total energy expend of RMEAAT is similar to SPT, and is the smallest. Because the data is forwarded along the shortest path without any aggregation expend in RMEAAT and SPT in the case of zero fusion degree and zero aggregation expend, as is shown in Fig.(a). When the fusion degree is close to 1, the energy expend of RMEAAT is consistent with that of BST, because RMEAAT is based on BST structure, and data is completely fused at every intersection without any aggregation expend, which makes the aggregation benefit more than 0, and data be transferred along the initial path of BST, as is shown in Fig.1(b).

![Figure 2](image2.png)

- The aggregation expend of unit data \( q_0 \) is assumed to be 15nJ/bit.

Fig.2(a)–(b) respectively show the total energy expend of MST, SPT, BST and RMEAAT when the fusion degrees are respectively equal to 0 and 1. From the simulation results, it can be seen that the energy expend of BST is still between that of SPT and MST. RMEAAT is superior to SPT when the fusion degree is close to 0. Because the aggregation benefits of all intersections are less than 0 in RMEAAT under the certain conditions, data is transmitted directly along the shortest path without any aggregation. Compared with SPT, RMEAAT can save much aggregation expend. Similarly, RMEAAT is also superior to MST when the fusion degree is close to 1. Because RMEAAT can dynamically adjust the number of aggregation nodes and the aggregation routing structure according to the aggregation benefit. If the aggregation benefit of intersection is less than 0, the transmission path of the node data is modified as the shortest path without aggregation any longer, which reduces the unnecessary
aggregation expend to a certain degree compared with MST. In addition, RMEAAT is better than BST, because BST only provides a static routing structure, but RMEAAT is based on BST structure and can dynamically adjust routing structure of BST according to aggregation benefit of intersection. Therefore, RMEAAT can adapt to the wireless sensor networks with the different fusion degrees.

For the second set of experiment, the maximum communication radius $R=30 \text{m}$. The range of $r_c$ is $[0.1 \text{m}, 1000 \text{m}]$, which can make fusion degree change from 0 to 1. The simulation chooses three aggregation expend of unit data $q_0$ to test different kinds of WSNs, which are respectively mild ($q_0 = 10 \text{nJ/bit}$), moderate ($q_0 = 60 \text{nJ/bit}$), and severe ($q_0 = 120 \text{nJ/bit}$). The final simulation results are the average value of 20 times in every experiment.

Fig.3(a)–(c) are respectively show the energy expend in the networks with different fusion degrees when $q_0$ is equal to 10 nJ/bit, 60 nJ/bit, and 120 nJ/bit. Compared with GIT, DAGP, and AFST, total energy consumption of RMEAAT respectively reduce about 15%, 18%, and 16% when $q_0 = 10 \text{nJ/bit}$, reduce about 28%, 37%, and 32% when $q_0 = 60 \text{nJ/bit}$, reduce about 38%, 47%, and 31% when $q_0 = 120 \text{nJ/bit}$. Therefore, RMEAAT algorithm has very good performance in the networks with larger aggregation expend, especially in the networks which need frequently transfer such complex monitoring data as voice, image, and video.

VII. CONCLUSION

This paper proposes an adaptive aggregation routing algorithm for WSNs with minimal energy consumption (RMEAAT), including aggregation expend and transmission expend. Firstly, it constructs an $\alpha - \text{BST}$ as the initial transmission path on the basis of MST and SPT. And then data are adaptively aggregated at every node along $\alpha - \text{BST}$ according to aggregation benefit: if aggregation benefit is greater than 0, data are aggregated; otherwise, not aggregated and directly transferred to sink along the shortest path. The simulation results show RMEAAT algorithm can effectively save energy and has a wide range of adaptability.

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