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ENERGY CONSUMPTION MODEL OF WIRELESS SENSOR NETWORKS BASED ON BANG-BANG OPTIMAL TIME CONTROL THEORY

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Abstract. *Energy consumption in wireless sensor networks is a key constraint for node-network lifetime, and how to extend its lifetime to improve the robustness of wireless sensor networks is currently a hot topic. This paper introduces the optimal time bang-bang control theory, and we achieve the status adjustment for a node by setting a certain threshold in the shortest possible time, which can reduce energy consumption and improve the lifetime of WSN. The final experiment shows that the application of the theory can enable energy model to obtain the optimal and prolong lifetimes of the node and network.*
Keywords: Wireless sensor networks, Network lifetime, Bang-bang control, Energy consumption

1. **Introduction.** Wireless sensor networks (WSNs) are usually self-organized wireless ad hoc networks comprising a large number of resource constrained sensor nodes, which gather data information through a large number of sensor nodes and send them toward a sink node, using multihop wireless communication. Because wireless sensors mostly are battery-powered, energy can be limited; furthermore, once the nodes are failure (energy depletion), it will be difficult to recycle, and efficient solutions should be proposed to extend the lifetime of the entire network.

In this paper, in order to minimize the network communication cost and achieve better balanced consumption throughout, we propose a dynamic efficient energy consuming method (ECO) based on bang-bang control theory. The main contributions of paper are as follows.

(1) First, we propose a method based on bang-bang control theory, which can control transfer of the data from bad status's node to energy enough node.

(2) We evaluate the proposed ECO algorithm, by comparing it with the state of art algorithms (leach and directed diffusion (DD)). The simulation results show that ECO is more efficient and effective in the presence of faulty and malicious nodes.

The remainder of this paper is structured as follows. Section 2 reviews the related work. In Section 3, the model of our proposed system is shown. Section 4 presents our effective ECO algorithm for routing and Section 5 shows our experimental results, respectively. Section 6 concludes our paper.

2. **Related Work.** In order to prolong the lifetime of a wireless sensor network, research on energy consumption of nodes is a focus in sensor network. At present, there are some methods of the energy consumption. Guo et al. [5] mainly analyze WiseMAC in different time periods, which include sending control packet time, transmission time, the transmitter and the receiving load packet conversion time. Finally, generated power is analyzed, and dynamic size is computed (as the network load size changes with change) under listening window, and ultimately the network load is determined. Although the literature is more careful analysis of the dynamic changes of WiseMAC listening window, the energy consumption of nodes is given out in each state, and its mathematical expressions are presented. The paper does not combine routing information and network topology information, but only for nodes of a single hop, and its energy consumption is obtained. This estimate of energy in the network is negligible. Polastre et al. [10] and Lin et al. [9] both are using linear programming model and a method of probabilistic analysis to obtain lifetime of upper or lower bound under assumptions. [10] assumes that the data interval presents exponentially distribution and load of each node obeys a Poisson distribution; thus, it will come to a conclusion that lifetime obeys Erlang distribution, but the model does not consider the state of a single node, so the consumption of the node is ignored due to idle listening. [9] only analyzes energy consumption model in the form; finally, the solved method does not give out. Rodoplu and Meng [13] propose an adaptive control mechanism in the MAC layer which can allow the sleep length of nodes to adapt changes of network traffic; meanwhile, in order to ensure that the node is awake when sending data, the protocol also proposes wake preamble based on WiseMAC, but the protocol had not RTS-CTS (request to send (RTS), clear to send (CTS)) mechanism, the synchronization mechanism and message passing mechanism, so it can reduce the energy consumption of the network. [10] proposed B-MAC protocol from the MAC layer aspect and analyzed the energy consumption. In one scheduling period, the energy consumption E will be divided into a transmitted energy consumption E_{sent}, received energy $E_{receive}$, a listener energy consumption E_{listen}, the data sampling energy consumption $E_{sampling}$ and sleep energy consumption E_{sleep}, and these can be expressed by Equation (1).

$$E = E_{sent} + E_{receive} + E_{listen} + E_{sampling} + E_{sleep} \tag{1}$$

Then each state's energy consumption is obtained by computing nodes in share of time, but the paper only considers the problem from the MAC layer while the energy consumption of the routing layer is ignored, although B-MAC protocol can adapt traffic control, but when energy analysis is done, they do not consider flow as a parameter and only analyze the energy consumption of single node in a scheduling period, when the scheduling period increases and the situation will become more complex. In summary, energy consumption issue for the wireless sensor network has caused widespread concern in the domestic and foreign researchers, but so far a more accurate, versatile and comprehensive energy model has not been come up with. Many researches still stay just in the MAC layer or the routing layer [1, 2, 14], while the energy consumption of WSN is mainly generated from the MAC layer and routing layer, and is affected and restricted by each other, but in recent years, many researchers have realized that cross-layer optimization of energy is more suitable for WSN, because through the integrated network, protocol stack can share information between different protocol layers and improve performance [3, 8]. Therefore, the analysis of energy consumption model must be combined with the MAC layer and routing layer, in order to take account of environmental factors and the packet loss in the actual network, packet loss rate is added in the network model, and it is a way to improve the accuracy of the model [11, 12]. However, this paper studies the routing protocol in routing layer, and the current common methods have LEACH clustering routing algorithm [6], and a data-centric routing algorithm (directed diffusion, DD) [7]. Nowadays the energy model for network traffic is a hot research, for network traffic directly affects energy consumption, so the accuracy of the model is higher, and the energy flow model is also more accurate. Existing researches mainly focus on state energy consumption of single node, but most of the length of time is calculated for each state in a particular protocol in a scheduling period of the share, and when the time tends to infinity, the formula does not hasten in general. This article will introduce the optimal time bang-bang control theory, and the use of the error threshold can promptly adjust the route to achieve energy optimization.

3. **System Model.** Bang-bang control was first proposed by Pontryagin [4], in optimal control problem for optimal target set, the known state equation of controlled system.

$$x(t) = f(x(t), t) + b(x(t), t)u(t) \tag{2}$$

Suppose meta of $f(x(t), t)$ and $b(x(t), t)$, $x(t)$ and t is continuously differentiable. The constraint condition of r-dimensional control vector $u(t)$ is expressed as Equation (3)

$$|u_j(t)| <= 1, \quad j = 1, 2, \ldots, r \tag{3}$$

From the initial state $x(t0) = x0$ starting, at one end of the state, time is $t > t0$, and it first reaches a moving target set $g(x(t), t) = 0$, where g is a p-dimensional vector function, which each meta $x(t)$ and t is continuously differentiable; meanwhile, the performance index $j[u(.)] = \int dt(t - t0)$ is the minimum. Optimal control $u(f)$ shall meet Equation (4)

$$\lambda'(t)b(x'(t), t)u'(t) = \min \lambda'(t)b(x'(t), t)u(t) \tag{4}$$

Let $H = f(x(t), t) + b(x(t), t)u(t)$, and then $\lambda'(t)$ will be expressed by Equation (5)

$$\lambda'(t) = -\frac{\partial H}{\partial x} = -\frac{\partial f(x(t), t)}{\partial x(t)} * \lambda(t) - \frac{\partial f(b(t), u)}{\partial x(t)} \tag{5}$$

where $\lambda(t) = \frac{\partial g(x(t),t)}{\partial x(t)} * u$, $x(t0) = x0$, $g(x(t), t) = 0$. This paper's target is minimum residual energy using bang-bang automatic control optimization. Within a certain period, we select node with minimal residual energy and those nodes will be closed or dormant status, then transfer their data to other nodes with high residual energy, and thus can constantly dynamically change routing path, thereby completing the low energy consumption, and prolonging the overall network lifetime. In this section we first present the necessary definitions and principles of energy consumption, and then give out the energy consumption model.

Definition 3.1. *Round: Defined as the time node taken to collect data for all the sensor nodes, and transfer data to SINK node.*

Definition 3.2. *Network lifetime: It is referred to the death of the first node in the network, and the number of rounds of the node survival is the network lifetime.*

4. **ECO Algorithm.** This section describes the energy bang-bang automatic control optimization algorithm ECO, where r represents the current round number, N represents that clusters are re-classified every N round, MEMID_LIST indicates cluster members list, CH_ID represents saved cluster header node ID, and AREA_ID expresses as node regional ID. ECO cluster header selection algorithm is as follows.

4.1. **The initial cluster head selection.** Each node arbitrarily selects a value from a random number between 0 and 1; if the value is less than the threshold T, then the node becomes the initial cluster header.

$$T = \begin{cases} \dfrac{p}{1 - p * \left(r * \bmod \frac{1}{p}\right)} & \text{if } N \in G \\ 0 & \text{others} \end{cases} \tag{6}$$

where p is the percentage of the number of cluster headers in total number of nodes, r is the number of rounds, and G is the overall collection for elected cluster header nodes in a round.
(1) If $r = 1$, all nodes send their residual energy and the location information directly to the sink node.
(2) If $r \bmod (N + 1) = 1$, cluster head collection and cluster structure are produced according to LEACH protocol, then sink broadcasts the cluster head and cluster structure, cluster head nodes set their own cluster member list MEMID_LIST, and non-cluster head nodes are saved as CH_ID; meanwhile, AREA_ID also is set as CH_ID, and then enters the data transfer process.
(3) If $r \bmod (N + 1)! = 1$, since the last round of the cluster heads has been designated as the next cluster head nodes, so in this one round all non-cluster head nodes (CH_ID! = ID) send the message to the corresponding cluster head, and became a member, when the cluster head receives the message and sends to all members, and then enters the data transfer phase.
(4) After data transfer is completed, if $r \bmod (N+1)! = 0$, all the non-cluster head nodes send their surplus energy to the cluster head, cluster head selects maximum residual energy node as the next cluster head, and broadcasts a message CH_MSG. Message contains the current cluster head identity CURCH_ID and the next cluster head identity NEXTCH_ID, receives broadcast messages member nodes, and compares CURCH_ID with AREA_ID. If the result is equal, then it shows cluster head node is the same area to the node, and then set the node CH_ID as NEXTCH_ID; if the result is not equal, then it illustrates the nodes and cluster head node are not in the same area, the message is ignored and the next one starts.
(5) After the data transfer is complete, if $r \bmod (N+1) == 0$, all non-cluster head nodes send residual energy and location information to their respective cluster heads, cluster heads send the position information and the remaining energy to the next cluster head or directly to the sink, and starts the next round. Because ECO is based on clustering scheme to partition, thus ensuring a more uniform distribution of cluster heads and the number of approximate optimal; meanwhile, it selects the max residual energy as a cluster head node, thus can avoid the more small residual energy to become cluster head node. And taking into account the energy consumption of each cluster may be different, ECO will repartition network to balance the energy consumption of the whole network.

4.2. **Inter-cluster routing.** Let r refer to the current round number, N represent re-cluster in every N round, CHHEAD_ID represent cluster head mark which can directly communicate with the sink, CHPARENT_ID show cluster head node ID of father, CHCHILD_LIST express its child cluster head list node identifiers, and inter-cluster routing of algorithm ECO is as follows.
(1) If $r \bmod (N + 1)! = 1$, at the beginning, each cluster head will send the remaining energy and location to sink.
(2) Sink calculates the average energy of all the cluster heads. We consider cluster head that the remaining energy is higher than the average energy as a candidate node, then calculate the distance between each cluster head and sink, then select a node as the nearest distance to sink and directly communicate with sink from the candidate nodes. We use bang-bang control to close or keep dormancy of the low energy nodes.
(3) Sink calculates the distance between any two cluster heads, and all cluster heads constitute a directed weighted graph G, which assumes that the distance between the cluster heads is smaller than d_0, the energy consumption of communication between cluster heads is suitable for free space channel model, the energy consumption will grow with the square of the distance, so right of two cluster heads is the square of distance, and then we use Dijkstra algorithm to find routes of the minimum communication cost between cluster

heads.
(4) n represents the number of cluster heads, V represents the set of cluster heads, and set the initial value as the other cluster head; S denotes the set of cluster head of the shortest path, and the initial value is empty; $rc[i][j]$ is the weight between v_i and v_j, and all V cluster heads are saved as CHPARENT_ID cluster heads' ID; D represents set of the shortest paths from the cluster head to other cluster heads.
(5) Select v_j, making $D[j] = MinD[i]|v_i \in (V - S)|$, v_j is the current one end obtained from the shortest path, so $S = S \cup j$.
(6) Modify the shortest path length v_k in set of V-S. If $D[j] + rc[j][k] < D[k]$, the modified $D[k]$ is $D[k] = D[j] + rc[j][k]$. Save the CHPARENT_ID of cluster head K as cluster head J's ID.
(7) Repeat (5) and (6) at a total of $n - 1$ times.
(8) Traverse through all the cluster heads, and save CHCHILD_LIST corresponding to cluster head CHPARENT_ID. Then broadcast CHPARENT_ID cluster head and CHCHILD_LIST. Each cluster head receives the message, and sets its own CHHEAD_ID, CHPARENT_ID to CHCHILD_LIST. Father node arranges timetable according to CHCHILD_LIST for the child, and the child node directly sends data to the father node in a specified time period. CHHEAD_ID node directly sends data from overall network to sink. Pseudo-code of ECO algorithm is as follows.

Algorithm 1: ECO algorithm

```
// Preprocessing stage
Initialize network;
round r = 0 ;
for i = number of unknown node, i = 0, i++ do
    Send message to sink for getting location and ID;
    Select a value t from random (0,1) for node i;
if t < T then
    Select node i as cluster header;
while set of cluster header node (T_h) is not NULL do
    if r = 1 then
        Send reside energy and location message to sink for getting location and ID;
    else
        Select last cluster header as next cluster header node;
    if r mod (n + 1)! = 1 then
        Send reside energy and location message to sink;
        Compute distance between cluster header nodes;
        Using bang-bang control to close or dormancy the low energy nodes;
        Get the optimal route;
    end for;
    end if;
    end if;
    end if;
    end while;
```

5. Experiment Results and Analysis.

5.1. Simulation metrics. The simulation process using nodes is randomly distributed in a square hook region $46 * 46$, the sensor node communication range $r = 2$, sink communication range $R = 20$, all sensor nodes have the same function, and there is a sink node. The initial energy of each sensor node is set to 0.5. In network simulation, we set several important parameters of the algorithm as shown in Table 1. The following results are the average of 10 runs of the simulation. It is noted that when the number of sensor nodes in the network is 1000, the node distribution is too loose, so we set node communication distance as 4 (free space), and in other cases the communication distance is 2.

5.2. Impact of node scale on network lifetime. Figure 1 shows the lifetime in the number of different sensor nodes. In the experiment, the number of nodes ranges from 1000 to 5000. When the number of nodes is 1000, ECO can obtain the largest lifetime which is 100, we can see that WSN lifetime has been continuously shortened as the number of nodes increases for three different routing algorithms, which is mainly due to expanding the node size. Network topology for WSN is more complex, the overall energy consumption is increasing, but the probability of a single node bottleneck also is increasing, which can lead to an overall shortening lifetime. In addition, as the proposed ECO algorithm uses the idea of bang-bang automatic control to effectively predict and find bottleneck sensor nodes, transfer data to another node with high residual energy. Thereby it can increase the overall lifetime, and compared with the other two traditional routing algorithms, our proposed algorithm can effectively extend the overall network lifetime.

5.3. The impact of error thresholds on network lifetime. Figure 2 shows the lifetime in different error thresholds, and the error number ranges from 1 to 9. With the error threshold increasing, the lifetime of the three routing algorithms continues to reduce; in

TABLE 1. Experiment setup

Parameter	Value
Node number	100
Sink number	4
Transmit range	15
Field	$40 * 40$

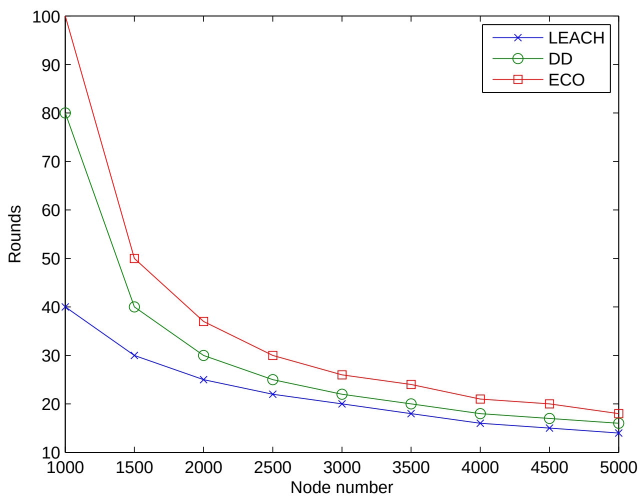

FIGURE 1. WSN lifetime in different nodes number

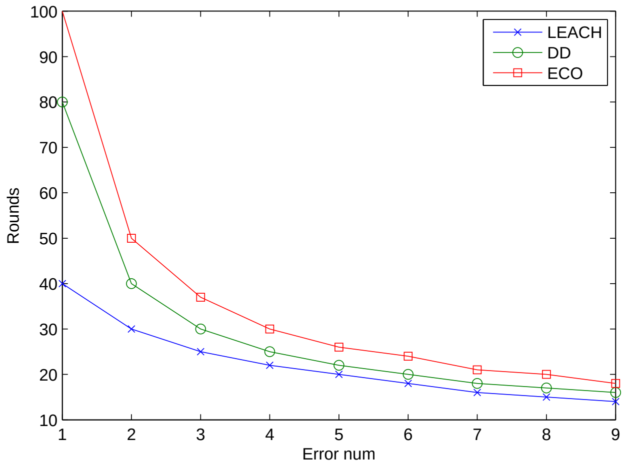

Figure 2. WSN lifetime in different error thresholds

particular, the error threshold is small, lifetime is larger, and it is the reason that an error threshold increasing will result in reducing closed and dormant nodes. Thus, the energy consumption will increase, the overall lifetime will prolong, and due to the use of bang-bang optimization time, our proposed ECO has a longer lifetime compared with the other two algorithms.

6. **Conclusions.** In this paper, we propose the ECO algorithm that reduced the energy consuming without requiring additional hardware cost. We use bang-bang control theory into our algorithm which can transfer the data to energy enough nodes according to the last energy. Our algorithm is beneficial for gathering data not only in situations of the case study, but also in many other applications in the real world. The validity of our method is confirmed by showing the simulation results with various conditions. It is observed that the proposed scheme has long lifetime in comparison with traditional algorithm. The future work focuses on the communication efficiency of ECO, and bang-bang control mechanism will be further improved in the ECO algorithm and tested in real network environment.

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