An Energy Efficient Cross-Layer Design for Wireless Sensor Networks

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***Abstract**- In wireless sensor networks, the multi-hop routing protocols can perform energy efficiency. However, the network lifetime still suffers degradations due to the unbalanced energy consumption for all nodes. Therefore, in this paper, with energy saving scheme we propose an improved cross layer algorithm to combining MAC and routing protocols to further prolong network lifetime.*

Keywords: Wireless sensor network, Cross layer, Energy efficiency, Routing protocol, Network lifetime.

1. Introduction

A The wireless sensor network (WSN) consists a large amount of sensing nodes which carry out sensing, computing and communicating capability to perform data gathering for the target area. Due to the small element of the sensing nodes, the computation and battery are limited to perform for long duration [1]. Besides, the sensing area always is not easy to reach to charge the battery of the nodes. Then the energy efficiency becomes one of most important issues for WSNs.

To perform energy efficiency for the data transmission, the multi-hop transmission is considered to be a main transmission scheme for WSNs. In the multi-hop scheme, most nodes need to sense and relay data to their neighbor nodes. The data fusion technique can integrate the data from different sources and deduct the redundant data, thus to decrease the transmission data to save energy consumption and lessen the transmission delay [2, 3]. Among the recent routing algorithm for MSNs, PEGASIS, PEDAPPA and BINARY [2-6] focus on the energy efficiency and prolong network lifetime. However, they suffer the severe transmission delay. Therefore, the shortest hop routing tree (SHORT) algorithm in [7] was been proposed for WSNs. The SHORT algorithms [7] construct some synchronous communication pairs with two nearest nodes and find the nearest nodes to relay the data. Comparing to PEGASIS, PEDAPPA and BINARY, the SHORT compromises both energy consumption and transmission delay and obtains better performance of "energy×delay". However, due to the random deployments of nodes, some active nodes perform redundant data sensing and further increase delay. Thus, the MAC layer protocol, turn off redundant node (TORN) in [8] let redundant nodes turn into sleep mode without degrading the network coverage and improve the data transmission delay. Therefore, the combining of SHORT and TORN (SHORTORN) can further compromise energy efficiency and transmission delay. However, due to the increasing average distance between the nodes after the TORN, the first exhausting energy node suffers the lifetime shrunk. Therefore, in this paper, we propose an improved SHORTORN to further prolong network lifetime and energy×delay.

2. Transmission Models

In this paper, the WSNs consist of a large amount of same sensing nodes which are uniformly random distributed in the sensing area. In the sensing area, the global positioning systems (GPS) are assumed to obtain the position of the nodes for the base station (BS). After the sensing nodes are deployed in the area, they are fixed and their battery can not be charged or changed. Each node can adjust the transmission power to communicate with other nodes.

Each active node sends one *k*-bits packet to its neighbor node in a round. The intermediate node receives data from other nodes and relays one packet obtained by data fusion to its neighbor node. In each round, any active node after sensing or data gathering always send out one *k*-bits packet via the communication pair. The data aggregation in the middle nodes receiving many packets generates one *k*-bits packet with assuming perfect data fusion.

Due to the energy limited in WSNs and the uncharged in the deployed nodes, to efficiently utilize the energy in the nodes is an very important issue for the WSNs. In MAC layer, the periodically sleep is usually scheme to saving the energy [11-13]. Therefore, there are two activity periods: active mode and sleep mode. In active mode, the sensors can communicate with the surrounding nodes. However, in sleep periods the sensor nodes stop the communication activity to save energy. Moreover, to further save the energy consumption, the data fusion scheme is used to reduce the redundant transmission data [2, 3].

In the physical layer of system model, the energy consumption for the amplifier circuit of transmitter and receiver is assumed by E_{elec} = 50nJ/bit. The transmission energy for the transmitter amplifier is assumed to be ε_{amp} =100 pJ/bit/m^2 [2, 3, 9]. Then, the energy requirement to transmit one packet of k bits for distance d can be expressed by

$$E_{Tx}(k,d) = kE_{elec} + kd^2\varepsilon_{amp}, \qquad (1)$$

where E_{elec} and ε_{amp} are the energy consumption of electric circuit and power amplifier of transmitter, respectively. Moreover, the energy consumption to receive one *k*-bit packet is expressed by

$$E_{Rx}(k) = kE_{elec}. \qquad (2)$$

3. Network Models

3.1 MAC Layer

The time division multiple access (TDMA) scheme is adopted in MAC protocol. To perform energy efficiency, the data is transmitted by multi-hop transmission, in which all farer nodes send their data via middle nodes toward to the sink. Therefore, all the communication links between two nodes should use different time slots to avoid collision. Moreover, some synchronous communication pairs with two nearest nodes is constructed and the time slots are firstly assigned for farer pairs. Then, the nearer communication pairs relay the data in the following time slot. Thus, the neighbor communication pairs do not use the same time slot.

Moreover, when there are several transmitters transmit packets to the same node, the TDMA divides the time slots for the receiving node to avoid the data collision.

3.2 Turning Off Redundant Node, TORN

Due to the limited energy of the nodes in WSNs and possibly high density of nodes distribution, the coverage of the nodes could be overlapping each other. Thus, those sensing nodes being redundant for sensing data can be turned into sleeping mode to save the energy [9,10].

In the TORN algorithm, all nodes initiate in the same time. The node's position can be detected by GPS and is broadcasted to the neighbor nodes. Then all nodes obtain the list all their neighbor nodes sorted by the distance form near to far. The list is call redundant neighbor list (RNL) [8]. After the sorting of the RNL, the nodes is determined to be active or sleep mode by contention. When one node obtains its active mode, it broadcasts this information to turn off its neighbors in the sensing range (SR). From one example of TORN as shown in Fig. 2, there are seven nodes in the area and node 2 is in the sensing range of node 1 and node 3. In Fig. 2, the RNLs for Node 1, 2 and 3 are then obtained as followings.

RNL of Node 1: *2*, 3, 4, 5, 7, 6,

RNL of Node 2: *3*, *1*, 4, 7, 5, 6,

RNL of Node 3: *2*, 1, 4, 7, 6, 5,

where the nodes with italic type are the RNs.

If node 1 got first transmission medium, it transmits the message of sleep mode to node 2. When node 2 receives the message, it will turn into sleep mode and broadcasts this information to the neighbors. While node 3 receives the sleep mode message from node 1 to node 2 or the message broadcasted by node 2, it removes the node 2 from its RNL. However, if node 2 accesses the transmission medium, both node 1 and 3 turn into sleep mode. Other nodes will also remove node 1 and 3 from their RNL. Therefore, the TORN algorithms can uniform the distribution of the nodes and not need to lower the density of nodes. After executing TORN, the nodes will become active nodes and sleep nodes to effectively lessen the energy consumption [8]. The active node 2 obtains its neighbor node list (NNL) as followings.

NNL of Node 2: 4, 7, 5, 6.

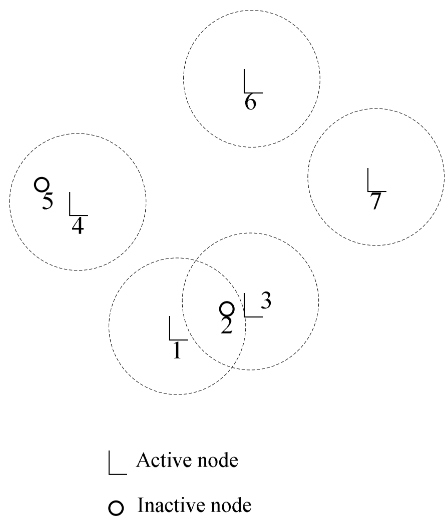


Figure 1. A TORN example.

Thus, the link 2-4 composes a communication pair from node 2 to node 4.

3.3 SHORT Algorithms

To efficiently perform data aggregation, three steps are adopted for efficient routing protocols [7]:

(1) Only one leader node is elected to transmit the gathering data to the BS.

(2) The sensing data packets are transmitted to the leader node via the shortest route.

(3) The data relaying performs most efficient data fusion technique to reduce the data redundancy.

In transmission, some nodes could be repeatly elected as the leader to consume the energy quickly. Thus, to balance the energy consumption, the leader should be evenly allocated to most nodes [3]-[5].

The delay time is defined as the data aggregation of all sensing nodes to the sink in a round. The delay is very important for some applications, for example, in the war field and some catastrophes. Thus, to reduce the delay time, in each time slot the communication pairs should be generated as many as possible. However, the maximum communication pairs depend on the numbers of the nodes [7].

In the SHORT algorithms [7], the BS is assumed being able to manage the network topology and perform the data aggregation with routing table and scheduling the time table. Fig. 1 shows an example of 5 nodes being performed communication pairs (CPs). To prolong the network lifetime, an energy coefficient for the leader selection, η_L, is defined. The BS select the leader node among all nodes by the maximal η_L. In SHORT, the energy coefficient is given by

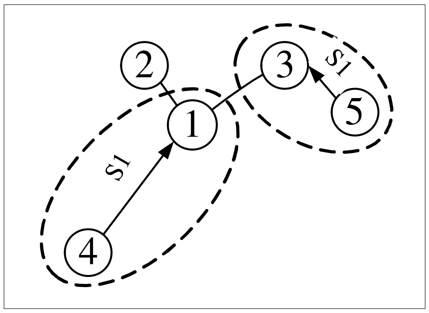
$$\eta_{L,S} = E_r/d_o^2 , \tag{3}$$

where E_r and d_o are the remaining energy of the target node and the distance between the BS and the target node, respectively.

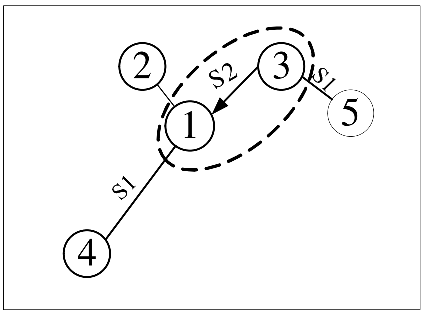
As the leader node is elected, the BS can manage the network topology and then inform the farer nodes to construct their communication pairs and schedule the time slots. For example, in Fig. 2, as node 1 is selected as leader, the BS ask the nodes 5, 4and 2 to make the communication pair to node 3, 1 and 1 respectively. Due to node 3 receives only one CP request, time slot S1 is assigned to CP(5,3). However, node 1 is requested by two nodes 4 and 2. Then the farer node 4 attains the higher priority to be assigned S1 and construct CP(4,1). Thus, node 2 got the S2 and make the CP(2,1).

With the assumption of the fully management capability to calculate the routing path computation and time slot schedule in Base station, there are most $\lfloor n/2^i \rfloor$ [1] CPs at the ith time slot for n nodes MSN. The least data delay would be $(\lceil \log_2(n) \rceil + 1)$ [1] for a complete data transmission for n nodes WSN. Therefore, in each time slot of SHORT algorithms, the CPs select the best neighbor nodes to transmit data and obtain the best time delay and energy efficiency.

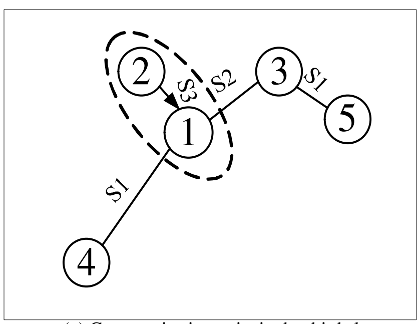
note1: $\lfloor\ \rfloor$ denotes the flooring operation. $\lceil\ \rceil$ denotes the ceiling operation.



(a) Communication pairs in the first slot ,
A is the leader.



(b) Communication pairs in the second slot ,
A is the leader.



(c) Communication pairs in the third slot ,
A is the leader.

Figure 2. The process of generating communication pairs under SHORT scheme [7].

4. Improved SHORTORN

At first, to investigate the energy efficiency of the SHORT algorithms we perform 2100 computer simulations in WSNs. To realize the number of nodes having been a leader (N_L) before the first node death (FND), we calculate N_L and the average lifetime of FND as shown in Table 1. From Table 1, it is evidently observed that the life time of FND is proportional to the N_L. That is, the larger the N_L, the longer lifetime.

Table 1. The average lifetime for the number of nodes been a leader before FND.

N_L	Average Lifetime	N_L	Average Lifetime
2	853	11	1608.9
3	982.3	12	1681.4
4	1066.1	13	1755.1
5	1122.3	14	1802.4
6	1204.3	15	1823.4
7	1276.8	16	1896.7
8	1386.3	17	1942.6
9	1477.1	18	2029
10	1540.4	19	2181.5
		20	2221.5

Therefore, to further improve the load balancing of leader for nodes in SHORT algorithm, in the improved SHORT algorithm we modify the energy coefficient for the leader selection, η_L, by

$$\eta_{L,\mathrm{IS}} = (C - N_L)E_r/d_o^2 , \quad (4)$$

where E_r and d_o are the same as in (3) and N_L is the number of a node which has been a leader. A maximal number been a leader, C, in (4) is used to balance the number of becoming a leader for nodes. Thus, when N_L of a node increases, the factor (C- N_L) decreases the possibility of the node to be a leader. Moreover, when a node has been leader C times, the factor (C- N_L) becoming zero will stop the node being a leader. Besides, if the factors (C- N_L) of all nodes become zero, the energy coefficient for the leader selection, η_L, in (3) will be used in the remainder lifetime for WSNs.

Furthermore, to maintain the coverage and reduce the data delay, the TORN scheme is combined to the SHORT algorithms, and we called it SHORTORN scheme.

5. Simulation Results

To verify the performance of WSNs lifetime prolonging scheme, computer simulation by Matlab programming is performed for SHORT, TORN and SHORTORN schemes. In our simulation, therefore are 50 sensor nodes uniformly distributed on a square area located at (0,0)-(100,100) with 100m×100m. The base station is deployed at (50,150). In all TORN schemes, the sensing range (SR) is set to 10 m to perform sufficient high coverage for WSN. In all node, the initial energy is all one joules. The perfect power control scheme to perform no error pack transmission is assumed for all nodes. The length of one packet is 2000 bits and energy consumption of transmission and reception is modeled by (1) and (2), respectively. The nodes are deployed randomly 30 times to find the sufficient statistics of performance in WSNs. As for the proposed SHORTORN schemes, the redundant nodes keep in sleep state until the active nodes is dead.

At first, we investigate the improvement of different weight C for SHOTORN schemes as shown in Figure 3. From Figure 3, it is observed that the proposed SHORTORN can prolong the lifetime of 30%, 50% and 100% nodes death (ND). However, due to the fewer nodes is active in SHORTORN, the mean distance of the CPs is longer than that of SHORT. Then, in SHORTORN the lifetime of the first node dead (FND) is shorter than SHORT.

After the energy coefficient for the leader selection, η_L is modified to (4), the lifetime of the first node dead (FND) of the improved SHORTORN is improved to outperform the SHORT scheme as shown in Table 2. From Table, it is observed that with C=100 the lifetime of FND is the best but with C=1000 the lifetime of 30% and 50% ND is the best. Therefore, with C=100, we further

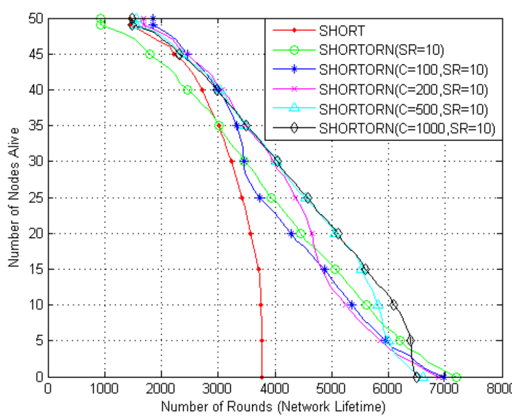


Figure 3. Lifetime performance for the SHORT and SHORTORN schemes

We compare the network lifetime gain of proposed SHORTORN over SHORT scheme for different weight C as shown in Figure 4. From Figure 4, it is observed that the maximal network lifetime gain of FND (2%ND) and LND (100%ND) is obtained at about C=60 and obtains more 33% and 85% lifetime than SHORT respectively. But for both 30% ND and 50% ND, the maximal network lifetime gain is obtained about at C=1000 and obtain more 17% and 33% lifetime than SHORT respectively. To compromise the network lifetime, we select C=100 for improved SHORTORN. Thus, the energy consumption and time delay comparisons for SHORT, proposed SHORTORN and improved SHORTORN schemes are shown in Table 3.

Table 2. Lifetime comparisons with different C for SHOTORN schemes.

Nodes / Lifetime / Protocol	2%	30%	50%	100%
SHORT	1447	3010	3416	3766
SHORTORN	933	3018	3941	7206
SHORTORN (C=100)	1857	3323	3726	6970
SHORTORN (C=200)	1689	3474	4365	6877
SHORTORN (C=500)	1561	3465	4547	6601
SHORTORN (C=1000)	1482	3486	4575	6502

From Table 3, it is observed that both proposed SHORTORN schemes outperform SHORT with the large improvement for both energy consumption and delay.

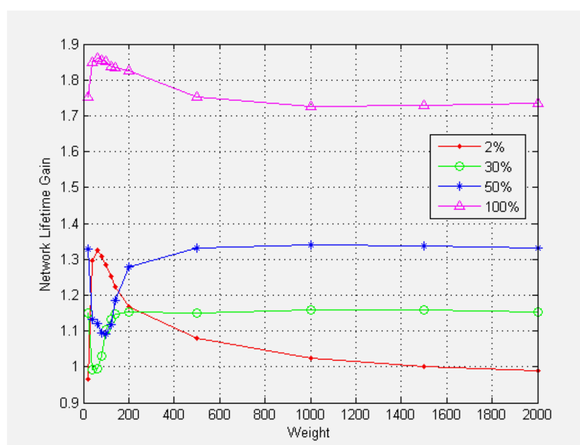


Figure 4. Network lifetime gain of proposed SHORTORN over SHORT scheme for different weight *C*.

Table 3. Energy and time delay comparisons with *C*=100 for SHORT, SHOTORN and improved SHOTORN schemes.

Performance Metrics		Improved SHORTORN	SHORT	SHORTORN
Energy Consumption (mJ / round)		7.3	13.3	7.0
Delay (slots per round)	Mean	5.0	6.81	5.02
	STD	0.30	0.05	0.33
Energy × Delay (Joule × slot)		0.0364	0.090	0.0354

6. Conclusions

In this paper, we investigate the energy efficiency for the WSNs by combing the routing algorithms SHORT and the MAC protocols TORN. To improve the balance energy consumptions for nodes, we select a maximal number of been leader to improve the SHORTORN. Simulation results show that the proposed improved SHORTORN not only prolongs network lifetime but also improve the energy efficiency and the data delay.

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