Optimizing Energy Consumption with Delay Constraint in Wireless Sensor Networks

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Abstract. Many existing energy efficiency protocols are proposed to address energy optimization for wireless sensor networks. However, most of them have weaken to take into account the factor of end-to-end delay. This paper investigates to find the best trade-off between two objectives: minimizing the energy consumption and end-to-end delay in wireless sensor network. We first propose a new energy-cost function for the inter-cluster routing algorithm. Next, we provide a *k*-least routes algorithm which is used to disseminate sensing data from cluster-heads to sink with minimum energy consumption subject to an end-to-end delay constraint. We evaluate the effectiveness of the energy balance between cost functions by simulation. In addtion, the extended simulations show that our proposal performs much better than similar protocols in terms of energy consumption and end-to-end delay.

Keywords: Energy consumption · End-to-end delay · Trade-off · Multi-hop

1 Introduction

Energy is the most crucial resource for wireless sensors, particularly in certain environments where replacing or recharging sensors' batteries is impossible. How to design an energy efficient routing protocol becomes the main objective for wireless sensor network (WSN). However, in many current applications of WSN like forest fire detection, data should be transmitted from sources to sink within a limited time. If it exceeds this limitation, data will not be useful anymore. Thus, a trade-off existing between energy consumption and end-to-end delay is extremely necessary.

The trade-off between energy consumption and delay in WSN have proposed by several recent works [1–3]. None of them obtain the optimum balance. The common network scheme of these protocols implements multi-hop approach. The advantage of this architecture is that it allows sensor nodes transmit data to the remote destination which is not in their transmission range by relaying on the other adjacent sensor nodes. This reduces energy consumption significantly and extends the lifetime of the network, but increases the end-to-end delay. However, the multi-hop communication from sensor

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nodes to sink does not take advantage of ability of data aggregation in network that reduces duplication of data between the adjacent sensor nodes whereas the data aggregation in the network is done very effectively by clustering method [4]. Therefore, in this study, we employ multi-hop routing approach for the clusterhead nodes that receive the sensed data from member nodes and then forward to sink through other clusterhead nodes. The clustering algorithm used in this study is what has been proposed by us in the most recent research [5]. Based on this model, we propose a new approach called DCEM (Delay Constrained Energy Efficient Multi-hop) to optimizing energy consumption with delay constraint in WSNs. Whereas the routing algorithm proposed in [5] is based on the aggregation cost function between energy consumption and end-to-end delay, the routing algorithm proposed in this study is based on the optimization method which finds the least energy-cost route satisfying end-to-end delay constraint. The major contributions of this reseach are followings:

– We propose a new energy-cost function to determine the most energy-efficient cost route for data dissemination from clusterheads to sink subject to an end-to-end delay constraint.
– We also provide a inter-cluster *k*-least routes algorithm which take into consideration both energy consumption and end-to-end delay.
– We present the simulation results to compare with other similar protocols.

The rest of the paper is organized as follows. In Sect. 2, we discuss related works for the same problem. Section 3 presents network and energy models. Section 4 describes our proposal in detail. We show simulation results in Sect. 5. Finally, Sect. 6 concludes this paper.

2 Related Works

In recent years, several works have proposed to figuring out the problem of energy efficient, delay-constrained routing in WSN.

In HEED [6], clusterheads are chosen out periodically based on a hybrid of the node residual energy and a secondary parameter, such as node proximity to its neighbors or node degree. HEED can achieve uniform clusterhead distribution across the network, but it needs many times of iterations to incur high overhead.

Akkaya and Younis proposed an energy-efficient protocol for delay-constrained data in [7]. This protocol allows packets relaying on multi-hop paths to minimizing energy consumption. Authors employ an packet scheduling method to guarantee the data delivery in real-time. Their approach, however, does not take into the delays that can occur in other layers.

Yingshu Li et al. studied the Minimum-Latency Aggregation Schedule problem in [8] to propose a collision-free transmission schedule of data aggregation for all sensors such that the delay for aggregated data to reach the sink is minimized. By constructing a Cluster-based Data Aggregation Tree, this protocol permits the packet transmissions among different clusters are concurrent and collision free. However, constructing distributed trees using broadcasting technique generates more overhead.

T.T Huynh et al. proposed an energy efficient delay-aware routing algorithm on the multi-layer WSN in [9], which sensors (clusterhead role) at each layer interconnected as de Bruijn graph model to improve network delay, energy consumption, and system reliability. Experimental results show outperformance of the delay and energy consumption.

Shi Bai et al. proposed an energy-constrained routing algorithm satisfying the bounded delay in [10]. This protocol allows packets are continuously distributed between the multiple paths with different delay constraints. It balances the diferential delay between the different paths by providing a polynomial-time algorithm. In addition, authors also proposed an approximation algorithm to solve the problem in general case. However, this algorithm requires quite a large buffer memory, which limits its potential application.

In [11], authors proposed a partial aggregation algorithm which can balance energy consumption and end-to-end delay using Markovian chain. This algorithm is designed to increase the rate of transmission and avoid from long delay. In [12], authors proposed a data forwarding protocol to finding the optimum trade-off between energy consumption and end-to-end delay by slicing communication range of sensors into concentric circles. Authors proved the proposed algorithm achieve near optimal on the *energy x delay* metric.

3 Network and Energy Model

3.1 Network Model

We employ the hierarchical network model for our proposal in Fig. 1. In this hierarchical network model, sensor nodes are distributed in local clusters. Each cluster itself elects

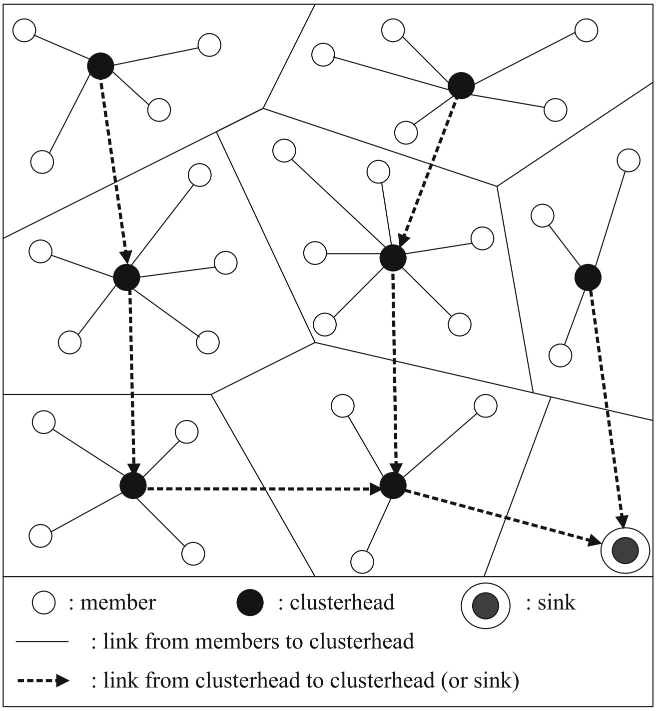

Fig. 1. Hierarchical wireless sensor network model.

a clusterhead that aggregates data from its members and sends fused data to the sink in the multi-hop manner. In addition, the clusterhead nodes also act as relays which forward packets to sink from the other clusterheads.

3.2 Energy Model

We verify a simplified model for the radio hardware energy dissipation in [13] to calculating energy costs for our enery model.

The energy consumption of each sensor member to sending l-bit data to its clusterhead is given by following equation:

$$E_{mem}(j) = l \times E_{elec} + l \times \varepsilon_{fs} \times d(j)^2 \tag{1}$$

where E_{elec} is the factor of electronics energy consumption, ε_{fs} is the amplifier energy to maintain an acceptable signal-to-noise ratio, $d(j)$ is distance from member j to its clusterhead.

The energy consumption of each clusterhead to fusing the all intra-cluster data from its members and transmitting data to other clusterheads is given by Eq. (2):

$$E_{CH}(i) = E_{Rx}(i) + E_{Fx}(i) + E_{Tx}(i) \tag{2}$$

where:

$$E_{Rx}(i) = l \times E_{elec} \times \left(size_{CH}(i) + relays\right) \tag{3}$$

$$E_{Fx}(i) = size_{CH}(i) \times E_{fuse} \times l \tag{4}$$

$$E_{Tx}(i) = \begin{cases} l \times (E_{elec} + \varepsilon_{fs} \times d^2) \times (1 + relays) & if\ d < d_0 \\ l \times \left(E_{elec} + \varepsilon_{mp} \times d^4\right) \times (1 + relays) & if\ d \geq d_0 \end{cases} \tag{5}$$

where $E_{Rx}(i)$ is the energy spent to receiving all intra-cluster data, $E_{Fx}(i)$ is the energy spent to fusing all intra-cluster data, $E_{Tx}(i)$ is the energy spent to transmitting l-bit data to other clusterhead or sink, $size_{CH}(i)$ denotes the number of member nodes which belong to the clusterhead i, $relays$ is the times of relay, E_{elec} is the factor of electronics energy consumption, ε_{fs} and ε_{mp} is the amplifier energies to maintaining an acceptable signal-to-noise ratio, d is the distance from clusterhead i to its next hop, $d_0 = \varepsilon_{fs}/\varepsilon_{mp}$ is the reference distance between transmitter and receiver.

Consequently, the total energy consumption for each round is:

$$E_{total} = \sum\nolimits_{i=1}^{K} E_{CH}(i) + \sum\nolimits_{j=1}^{N-K} E_{mem}(j) \tag{6}$$

where K is the number of clusterheads, N is the number of sensors in the network.

4 Delay Constrained Energy Efficient Multi-hop Routing

In this section, we describe DCEM protocol in detail. Operation of DCEM is divided into consecutive rounds. Each round starts with network construction phase consisting of establishment of clusters and designation the delay-constrained energy-efficient route from clusterheads to the sink, followed by data transmission phase from sensor nodes to sink based on findings from previous phase.

To establishing clusters, we use the algorithm was proposed in our recent study. This algorithm is described in [5]. In the following section, we propose the cost function and the routing algorithm to balance the energy consumption and guarantee end-to-end delay in WSN.

4.1 Link and Route Cost Functions

We define the following cost function for a link between clusterhead nodes *i* and *j*.

$$cost_{ij} = \left(E^i_{Rx} + E^i_{Fx} + E^i_{Tx}\right) \times cost\left(E^i_{Re}\right) \tag{7}$$

where E^i_{Rx} is the energy that clusterhead *i* spent for receiving *l*-bit data from member nodes, given by Eq. (3). E^i_{Fx} is the energy that clusterhead *i* spent for fusing *l*-bit data from *m* member nodes, given by Eq. (4). E^i_{Tx} is energy spent for transmission of a *l*-bit data from clusterhead *i* to clusterhead *j* over distance *d*, given by Eq. (5).

And $cost(E^i_{Re})$ is cost function which takes into consideration the remaining energy of sensors for the energy balance among sensors. Therefore, the function $cost(E^i_{Re})$ is based on the principle in which small changes in remaining energy of sensors can result in large changes in value of cost function. Exponential function $f(x) = e^{(1/x^2)}$ is the kind of function that can satisfy the this principle [14]. Replacing *x* by E^i_{Re}(the remaining energy of sensor *i*), we have the following cost function:

$$cost(E^i_{Re}) = exp^{\left(1/\left(E^i_{Re}\right)^2\right)} \tag{8}$$

To calculating the cost function for a route from clusterhead node *x* to sink *s*, we define the following equation:

$$Cost(x, s) = \sum\nolimits_{i,j \in \{x,U,s\}} cost_{ij} \tag{9}$$

where *U* is set of intermedia nodes from clusterhead *x* to sink *s*.

4.2 Inter-Cluster Multi-hop Routing Algorithm

Our optimization problem is finding the least-cost route (most energy-efficient route) from a clusterhead node *x* to the sink *s* such that the end-to-end delay along that route does not exceed a delay constraint Δ. The constrained minimization problem is:

$$\min_{R_k \in R'(x,s)} Cost(R_k) \tag{10}$$

where R_k is the k^{th} route, $R'(x,s)$ is the set of routes from clusterhead node x to the sink s for which the end-to-end delay is bounded by Δ, given by:

$$D_{ete}(R_k) \le \Delta, R_i \in R'(x,s) \tag{11}$$

where $D_{ete}(R_k)$ is the time elapsed between the departure of a data packet from a source x of the k^{th} route and its arrival to a sink s. We defined this delay in [5] by following equation:

$$D_{ete}(x,s) = \sum_{i,j \in \{x,U,s\}} \left(\left(\frac{1}{\mu - \lambda} \right) + \frac{1}{\psi} + \frac{d_{ij}}{\gamma} \right) \tag{12}$$

where μ, λ, ψ, and γ are constants with assumption that they are same for all clusterheads, l is the packet size (bits), ψ is the link bandwidth (bps), d_{ij} is the length of physical link from clusterhead i to clusterhead j, and γ is the propagation speed in medium (m/sec), U is set of intermediate nodes from clusterhead x to the sink s.

Input: clusterhead nodes x, sink s, energy and postion of x, position of s.

Output: the best route with minimum energy consumption and match the end-to-end delay.

```
1. SeR = ∅; //The selected route to disseminate data from clusterhead x to the sink s.
2. NoSa = ∅; //Set of routes that is not satisfy the delay bound Δ.
3. Calculate cost_ij, ∀i, j∈C; //C is set of clusterhead nodes, j can be sink.
4. Calculate K(x,s); //Number of probable routes from clusterhead node x to the sink s.
5.  while(k ≠ K(x,s)) // initial k =1
    {
6.    Find k-least cost routes kSR(x,s,k);
7.    R_k = kSR(x,s,k) \  NoSa; //R_k is the k^th least-cost route
8.    Calculate D_ete(R_k) from equation (7);
9.    If D_ete(R_k) ≤ Δ Then SeR = R_k;
10.   Else {
11.            NoSa = NoSa ∪ R_k;
12.            k = k +1;
           }
    }
13. Return SeR;
```

Fig. 2. Pseudo code for DCEM algorithm.

By considering the optimization problem above, we propose the algorithm shown in Fig. 2 to find *k*-least cost routes that meet the end-to-end delay constraint.

The algorithm calculates the $cost_{ij}$ (line 3) for each link from clusterhead *i* to clusterhead or sink *j* based on the cost function defined in Eq. (7). Then, it calculates the number of probable routes from clusterhead node *x* to the sink *s* (line 4) using Depth-first search (DFS) algorithm in [15]. In line 6, the algorithm uses the *k*-shortest path in [16] to find *k*-least cost route (initial $k = 1$) based on Eqs. (7), (8) and (9). After determining the least-cost route, R_k, the algorithm calculates the end-to-end delay $D_{ete}(R_k)$ for that route using Eq. (12). Then, it checks whether this end-to-end delay satisfy the specified threshold value Δ or not. If so, R_k is chosen (SeR, line 9), if not, R_k will be removed and added to the NoSa (line 11). Line 7 will remove least-cost routes that are not satisfy the delay bound Δ.

5 Simulation Results

We use MATLAB 8.1 to evaluating the effectiveness of our proposal. The simulation parameters are summizied in Table 1.

Table 1. Simulation parameters.

Parameter	Value
Network size	100 m x 100 m
Number of sensor nodes	100 nodes
Sink location	(50, 50)
Size of data packet	30 bytes
λ	3
μ	6
Initial energy of each node	1 J
E_{elec}	50 nJ/bit
ε_{fs}	10 pJ/bit/m^2
ε_{mp}	0.0013 pJ/bit/m^4
E_{fuse}	5 nJ/bit
ψ	40 bps
γ	50 m/s.

In Sect. 4, we have proposed an new energy-cost function to determine the least-cost route for data dissemination from clusterheads to sink. In the first simulation, we want to show the primacy of the cost function that we have proposed in Eqs. (7), (8) and (9) as compared with the previous cost functions. In [17], instead of using the consumed energy e_{ij} as the cost function presented in [18], when a packet is transmitted between node *i* and node *j*, the link cost is essentially equivalent to function $cost_{ij} = \frac{e_{ij}}{E_i}$ where E_i

is the remaining energy of node i. We compare the network lifetime using different cost functions which are $cost_{ij} = e_{ij}$ [18], $cost_{ij} = \frac{e_{ij}}{E_i}$ [17] and $cost_{ij}$ proposed in Eqs. (7), (8).

In Fig. 3, we evaluate the number of dead nodes through each round. As can be seen in Fig. 3, the line represented by the equation $cost_{ij} = e_{ij} + exp(1/E_i^2)$ shows that the number of dead nodes increases slowly in the first rounds but increases rapidly in the last rounds. Whereas, number of dead nodes in lines represented by equations $cost_{ij} = e_{ij}$ and $cost_{ij} = e_{ij}/E_i$ increases steadily over time.

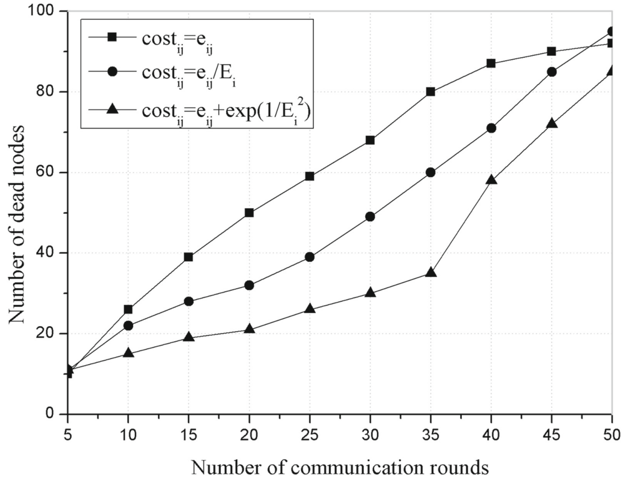

Fig. 3. Compare the energy balance of different cost functions in terms of number of dead nodes over time.

In Fig. 4, the line represented by the equation $cost_{ij} = e_{ij} + exp(1/E_i^2)$ shows that the total consumed energy increases rapidly increases slowly in the first rounds but increases slowly in the last rounds. Whereas, total consumed energy in lines represented by equations $cost_{ij} = e_{ij}$ and $cost_{ij} = e_{ij}/E_i$ increases steadily over time. These results are explained by the exponential function of the remaining energy that we applied in cost function. This function, $cost(E^i_{Re})$ in Eq. (8), makes the large change in value of cost function as remaining energy of sensors changes a few. Thus, it balances the energy consumption among clusterhead nodes and maximizes network lifetime.

In the second simulation, we evaluate the performance of the DCEM protocol comparing with LEACH in [13] and HEED in [6]. We run 5 experiments which was performed in 20 rounds (each round is 1 s). Each experiment is assigned a distinctive end-to-end delay constraint (we set the bounded delay Δ from 10(ms) to 50(ms) for experiments respectively). The results are shown via Figs. 5 and 6.

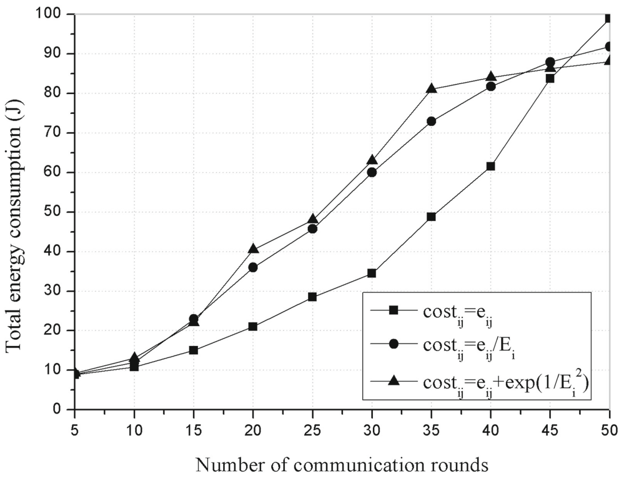

Fig. 4. Compare the energy balance of different cost functions in terms of total energy consumption over time.

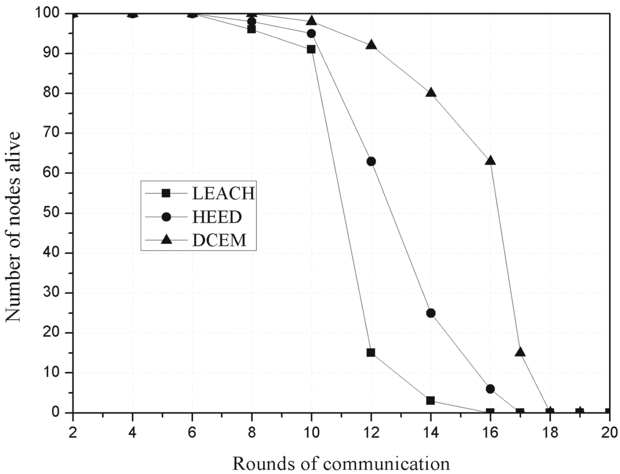

Fig. 5. Performance of LEACH, HEED, and DCEM on number of nodes alive with respect to given delay constraint.

In Fig. 5, the result is the average value of 5 experiments. For LEACH, each node i elects itself to become a clusterhead with probability $CH_{prob}(i) = \left(\frac{E_i}{E_{total}} \times k, 1\right)$, where E_i is the remaining energy of node i, and $E_{total} = \sum_{i=1}^{N} E_i$. For HEED, the optimal number of clusterheads k_{opt} is computed to using as an initial percentage of clusterheads. This may result in slower death of sensor nodes. LEACH and HEED are organized for multihop networks, however, neither of them take interest in the end-to-end delay

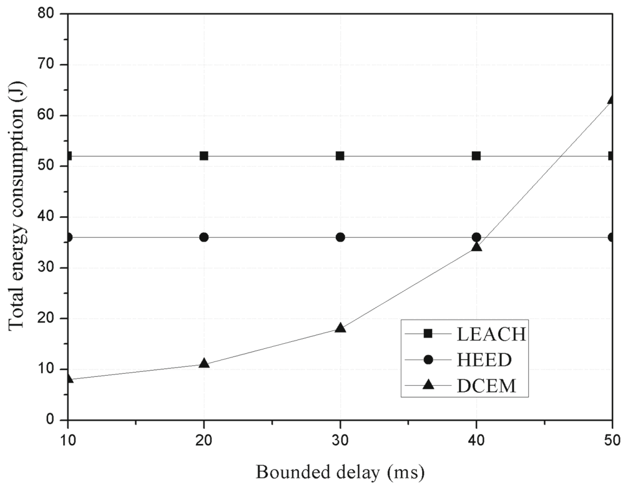

Fig. 6. Performance of LEACH, HEED, and DCEM on Total Energy Consumption with respect to different delay constraints.

constraint. Thus, sensor nodes just send data to the sink following the established time slot in the first phase (cluster setup phase) regardless of the end-to-end delay requirement of the application. Therefore, the total energy consumed by the data transmission for DCEM is significantly less than for both LEACH and HEED. This results in faster death of sensor nodes after each round for both of LEACH and HEED comparing with DCEM as shown in Fig. 5.

In Fig. 6, the total energy consumption of both LEACH and HEED is constant for any values of the bounded delay Δ (37 J for HEED, 52 J for LEACH). Whereas, for DCEM, the total energy consumption increase as the bounded delay Δ increases. Especially, when the $\Delta \geq 70$(ms), the total energy consumption increase rapidly.

6 Conclusions

In this research, we have proposed a new cost function for the inter-cluster *k*-least cost routes algorithm. Thenceforth, we have provided a multi-hop routing algorithm from clusterheads to sink with minimum energy consumption subject to an end-to-end delay constraint. By simulation, we have evaluated our cost function compared with other functions in terms of energy balance. In the expansion work, we have shown the outstanding performance of our proposal by comparing with other protocols in terms of network lifetime and energy consumption respect to different delay constraints.

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