

Multi-Hop Deterministic Cluster Routing in Wireless Sensor Networks

Sang Hyuk Kang*

ABSTRACT

We investigate the effects of applying multi-hop forwarding to deterministic cluster routing on energy efficiency. The base station node constructs a deterministic multi-hop routing tree by comparing energy expenses between direct single-hop forwarding and multi-hop relaying. Considering the whole-path energy expense for multi-hop routing, we adopt a dynamic programming to achieve energy efficiency based on global optimization. Our deterministic multi-hop relaying improves existing deterministic cluster routing in terms of network lifespan, which is shown by simulations.

Key Words : Wireless sensor network, cluster routing, deterministic, multi-hop, energy saving.

I. Introduction

Wireless sensor networks (WSN) require sophisticated energy-efficient routing protocols to prolong the network lifespan. Renowned LEACH^[1] and most of its descendant algorithms^[2] adopt conventional stochastic cluster routing. Instead of stochastic cluster routing, there has been recent research work on deterministic cluster routing^[3,4] with longer network lifespan by eliminating the stochastic nature and/or control messages.

In the research by Choi,^[5] they have proposed a stochastic cluster routing with a multi-hop forwarding among cluster head nodes, based on a local optimization of the energy expense. However, we can hardly find work on multi-hop routing for deterministic cluster routing. In this letter, we investigate the

effects of applying multi-hop routing to a deterministic cluster routing^[4] on energy efficiency. Our main contribution is providing a dynamic programming by considering the whole-path energy expense for multi-hop routing to achieve maximum energy efficiency based on global optimization.

II. Deterministic Cluster Routing

In this section, we redescribe the existing deterministic cluster routing (DCR)^[4] by the notations used in this letter. There are N battery-powered sensor nodes which are elements of the sensor node set $M = \{n_1, n_2, \dots, n_N\}$. Considering the base station (BS) as a special node, let us denote it by n_0 . We define the extended set of nodes, $\tilde{M}$, by adding the BS node to the sensor node set M , as $\tilde{M} = \{n_0, n_1, n_2, \dots, n_N\}$. Sensor nodes are randomly deployed on a circular-shaped sensor field with radius $L[m]$.

By exchanging initial greeting messages, each node in $\tilde{M}$ has acquired the distance between itself and all other nodes. Let d_{ij} denote the distance between nodes n_i and n_j in $\tilde{M}$. The distance information $\{d_{ij} | n_i, n_j \in \tilde{M}\}$ among the sensor nodes is reported to the BS. Note that the distance between the BS and each sensor node, $\{d_{0,i} | n_i \in M\}$, can also be measured by the BS itself. Gathering all distance information from the sensor nodes, the BS constructs routing paths by performing the functions of deterministic clustering with node re-indexing and deterministic TDMA-scheduling. The resulting deterministic routing information is broadcast to all of the sensor nodes.

N sensor nodes are divided into K equal-size clusters. We have the cluster set $C = \{c_1, c_2, \dots, c_K\}$. Each cluster, c_k , is a set of $G = N/K$ sensor nodes. For the sake of simplicity, we assume that G is an integer. By the BS, sensor nodes close to each other are assigned into the same cluster. Sensor nodes n_i are re-indexed with new node-indices i , such that $c_1 = \{n_1, n_2, \dots, n_G\}$; $c_2 = \{n_{G+1}, n_{G+2}, \dots, n_{2G}\}$; and so on. Consequently, cluster c_k ($k = 1, 2, \dots, K$), is the set of sensor nodes with new indices, such as

* This work was supported by the 2024 Research Fund of the University of Seoul.

• First Author : The University of Seoul, School of Electrical and Computer Engineering, shkang@uos.ac.kr, 종신회원
논문번호 : 202408-169-B-LU, Received August 7, 2024; Revised August 20, 2024; Accepted August 20, 2024

$$c_k = \{n_{(k-1)G+1}, n_{(k-1)G+2}, \dots, n_{kG}\}. \quad (1)$$

From now on, we refer to nodes n_i by the newly assigned node indices i , ($i = 1, 2, \dots, M$).

On the other hand, the time line of cluster routing consist of rounds, r_m ($m = 1, 2, \dots$). According to DCR,^[4] for round r_m , the cluster head (CH) node of cluster c_k is determined to be node $n_{h_m(k)}$, in which the node-index $h_m(k)$ is

$$h_m(k) = (k-1)G + (m-1)\%G + 1, \quad (2)$$

where % is the modulo operation. During a round, a CH node receives sensor data from all of its member nodes, aggregates the data, and forwards it to the BS node directly in single-hop transmission.

III. Multi-Hop Deterministic Cluster Routing

In this section, we describe our proposed method for applying multi-hop forwarding among the CH nodes to deliver aggregated sensor data to the BS node. Transmitting an l_d -bit data to the receiver at a distance d [m], a sensor node consumes energy $E_T(l_d, d)$ [J] by^[1]

$$E_T(l_d, d) = \begin{cases} l_d(E_e + \epsilon_f d^2), & \text{if } d < \delta \\ l_d(E_e + \epsilon_m d^4), & \text{if } d \geq \delta \end{cases} \quad (3)$$

where E_e [J/bit] is the energy factor in the circuitry; ϵ_f [J/bit/m²] and ϵ_m [J/bit/m⁴] are the energy dissipation factors in the transmission amplifier by free space model and the multi-path model, respectively; and $\delta = \sqrt{\epsilon_f/\epsilon_m}$ [m]. Energy consumption in a sensor node receiving l_d -bit data is $E_R(l_d)$ [J] as

$$E_R(l_d) = l_d E_e. \quad (4)$$

In conventional LEACH-based single-hop cluster routing, a CH node transmits the aggregated sensor data to the BS directly. This approach causes the nodes far from the BS to suffer greater energy depletion, which results in a short network lifespan. A multi-hop routing scheme allows a CH node to take other CH nodes as relay nodes in transferring data to the BS

in order to reduce energy consumption.

We consider sensor- node energy consumption as follows. When l_d -bit data is transmitted from sensor node n_i to other sensor node n_j ($n_i, n_j \in M$), the energy expense $e(n_i, n_j)$ is the Tx energy consumed in n_i plus the Rx energy consumed in n_j . For transmitting data from a sensor node to the BS, we only consider the Tx energy consumption. We consider Rx energy for transferring data from the BS to as sensor node. Consequently, we have the following for the sensor-node energy expenses as follows.

$$e(n_i, n_j) \triangleq \begin{cases} E_T(l_d, d_{ij}) + E_R(l_d), & (i \neq j, n_i, n_j \in M) \\ E_T(l_d, d_{i0}), & (j = 0, n_i \in M) \\ E_R(l_d), & (i = 0, n_j \in M) \\ 0. & (i = j, n_i, n_j \in \tilde{M}) \end{cases} \quad (5)$$

From eqs. (3) and (4), we have $e(n_i, n_j) = e(n_j, n_i)$ for ($n_i, n_j \in M$). We also use the following notation for short.

$$e_{ij} \equiv e(n_i, n_j).$$

In a recent investigation into multi-hop cluster routing by Choi,^[5] they have proposed a stochastic cluster routing with a multi-hop forwarding scheme based on a least cost tree by local optimization of the route, as shown in Fig. 1(a), where the next-hop node of node n_i is determined by comparing energy expenses between direct forwarding to the BS, e_{i0} , and indirect forwarding via other CH nodes n_p , $e_{ip} + e_{p0}$, in which the next-hop node n_p is assumed to perform direct forwarding to the BS with e_{p0} . This may results in a local optimization scheme.

However, the concept of our approach is shown in Fig. 1(b), where the energy comparison is carried out by comparing the energy expense of the direct transmission e_{i0} with $e_{ip} + \tilde{e}_p$ in which $\tilde{e}_p$ is the total energy expenses along the whole-path of the optimum multi-hop route from the next-hop node n_p to the BS. From this, we expect to achieve global optimization.

We explain our proposed deterministic multi-hop scheme in detail. In the location phase of the deterministic cluster routing, the BS node performs a

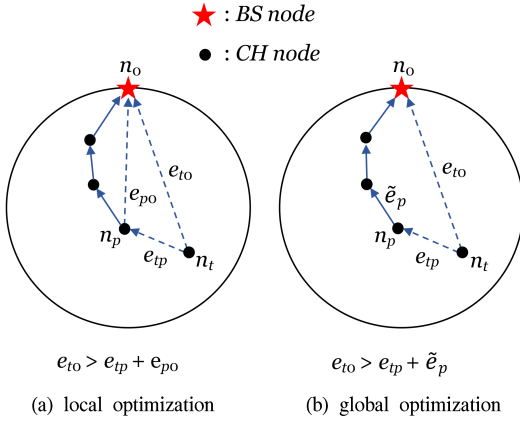


Fig. 1. Multi-hop path selection

newly added function called *deterministic multi-hop path setting* as explained in the following.

For each of the first G rounds r_m ($m = 1, 2, \dots, G$), the BS constructs the CH-node list H_m with K elements,

$$H_m = [n_{h_m(1)}, n_{h_m(2)}, \dots, n_{h_m(K)}], \quad (6)$$

in which the node-indices $h_m(k)$ for ($k = 1, 2, \dots, K$) is determined by eq. (2). The BS constructs the optimal-path energy cost list with K elements, each of which is the total energy expenses along the whole-path of the optimum multi-hop route from each CH node in H_m to the BS,

$$\tilde{E}_m = [\tilde{e}_{h_m(1)}, \tilde{e}_{h_m(2)}, \dots, \tilde{e}_{h_m(K)}]. \quad (7)$$

The list $\tilde{E}_m$ is initialized to be the energy expenses for direct forwarding to the BS, i.e., $\tilde{e}_{h_m(k)} = e(n_{h_m(k)}, n_0)$ in the beginning. We have another K -element list called the next-hop list F_m in which each element $F_m[k]$ is the next-hop CH node for each CH node $H_m[k]$. We denote F_m as

$$F_m = [n_{f_m(1)}, n_{f_m(2)}, \dots, n_{f_m(K)}]. \quad (8)$$

Each element of F_m is initialized to be the BS node, as $n_{f_m(k)} = n_0$, ($k = 1, 2, \dots, K$), in the beginning.

After above initialization, the lists $\tilde{E}_m$ and F_m are updated iterating the following process. For the first element of H_m , $H_m[1] = n_{h_m(1)}$, which is the CH node

of cluster c_1 , the energy expense for the direct-forwarding to the BS, $e(H_m[1], n_0)$, is compared with the energy expenses through other CH nodes in H_m by taking the optimal-path energy $\tilde{E}_m$ for the relay nodes. The first element of $\tilde{E}_m$, which is for node $n_{h_m(1)}$ is updated as

$$\tilde{E}_m[1] = \min_{H_m[k]} \{e(H_m[1], H_m[k]) + \tilde{E}_m[k]\}. \quad (9)$$

At the same time, the next-hop CH node $F_m[1] = n_{f_m(1)}$ for $n_{h_m(1)}$, whose index $f_m(k)$ is updated as well, such that

$$F_m[1] = \arg \min_{H_m[k]} \{e(H_m[1], H_m[k]) + \tilde{E}_m[k]\}. \quad (10)$$

With this, updating $\tilde{E}_m[1]$ and $F_m[1]$ for $H_m[1]$ are done. The same procedure is then carried out for CH node $H_m[2] = n_{h_m(2)}$ to update $\tilde{E}_m[2]$ and $F_m[2]$, and so on.

In the following, we have a pseudo code for the above explained dynamic programming represented as ‘Updating Loop’. Once the updating processes for all elements of $\tilde{E}_m$ and F_m are done by the first iteration of the updating loop in the pseudo code, we are given the next-hop tree as a *local optimization* as in Fig. 1(a), because the initial value of the elements in $\tilde{E}_m$ was the energy for direct forwarding to the BS. If the BS keeps iterating the updating procedure several times until the list $\tilde{E}_m$ converges to its optimum value, it is given by the *global optimization* as in Fig. 1(b). The global optimization requires several loops to converge, it has more complexity than the local optimization with a single loop in the algorithm, which may affect the real-time routing in stochastic cluster routing with varying CHs round by round. However, since we consider deterministic cluster routing, this multi-hop path selection can be carried out in advance before the network operation starts, without compromising the real-time performance.

The next-hop determination process explained so far is carried out for rounds r_m or r_1 through r_G . We note that all deterministic routing processes from round r_1 through r_G are the same as from round r_{G+1} through r_{2G} , and as in every G rounds. In other words,

the constructed routing tree for $r_m(m=1, 2, \dots, G)$ is the same as in rounds from then on $r_s(s=G+1, G+2, \dots)$ with $s \% G = m$. We have a pseudo-code of next-hop determination among CH nodes for the first G rounds, $r_m(m=1, 2, \dots, G)$ in the following.

Algorithm: Deterministic Multi-Hop Path Setting

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for  $m = 1$  to  $G$  do
  /* Initialization */
  for  $k = 1$  to  $K$  do
     $h_m(k) \leftarrow (k-1)G + (m-1)\%G + 1$ 
     $H_m[k] \leftarrow n_{h_m(k)}$ 
     $\tilde{E}_m[k] \leftarrow e(H_m[k], n_0)$ 
     $F_m[k] \leftarrow n_0$ 
  end for
  /* Updating Loop */
  do
    for  $l = 1$  to  $K$  do
       $k_o \leftarrow \arg \min_k \{e(H_m[l], H_m[k]) + \tilde{E}_m[k]\}$ 
      if  $k_o \neq l$  do
         $\tilde{E}_m[l] \leftarrow e(H_m[l], H_m[k_o]) + \tilde{E}_m[k_o]$ 
         $F_m[l] \leftarrow H_m[k_o]$ 
      end if
    end for
  until  $\tilde{E}_m$  converges
end for

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Once the BS constructs the multi-hop tree by determining the next-hop nodes of all CH nodes, it broadcasts the information to the sensor nodes. In single-hop cluster routing, once a CH node forwards data generated within its cluster to the BS, then it can go to sleep. However, in multi-hop routing, it cannot go to sleep until the BS, after receiving all required sensor data, allows the CH nodes to go to sleep.

From simulations, it is observed that our proposed dynamic programming scheme converges to the same routing path as Dijkstra's routing algorithm^[6] which also yields global optimization.

IV. Performance Evaluation

We evaluate our proposed multi-hop deterministic cluster routing (MH-DCR) by comparing it to the deterministic cluster routing (DCR)^[4]. Simulations are

carried out on NS-2 in the scenario of $\{N=240, L=87[m]\}$ with $K=12$ clusters. Simulation parameters are as follows^[1,4]. We set $I_d=500[\text{bits}]$ and $E_e=0.2[\text{nJ/bit}]$. Data is transmitted at 1Mbps on 2.4GHz signal, which gives $\varepsilon_f=60 [\text{pJ/bit/m}^2]$ and $\varepsilon_m=0.0013 [\text{pJ/bit/m}^4]$. Every node has initial energy of $0.2[\text{J}]$.

We show the number of nodes alive versus rounds in Fig. 2. For reference, we have shown the result of the conventional LEACH^[1]. Both the deterministic cluster routing (DCR)^[4] and our proposed multi-hop deterministic cluster routing (MH-DCR) run more rounds compared with LEACH. We look at running rounds until 200 nodes are alive as shown by the dashed horizontal line. In the MH-DCR multi-hop setting algorithm, the updating procedure for $\tilde{E}_m$ and F_m converges after 4 iterations as global optimization. In the figure, MH-DCR with local optimization with 1 iteration is observed to have run about 475 rounds by the 200-node criterion. The result of global optimization for MH-DCR yields about 515 rounds, which is 8.4% improvement over the local optimization in our simulation scenario of $\{N=240, L=87[m], K=12\}$. DCR shows about 340 rounds by the 200-node criterion. MH-DCR schemes, running at least 475 rounds, yield more than 38% improvement over DCR. From simulations, our proposed method shows efficiency with energy expenses of $16.4[\text{mJ}]$ per round as in MH-DCR(global), and outperforms DCR with $21.9[\text{mJ}]$ which is a single-hop scheme. If we look at the lifetime as the time until the last-node's death, DCR shows the longest result, which is often observed when comparing single-hop algorithms with multi-hop algorithms. This can be expected from the fact that the nodes near the BS have short lifespan by relaying

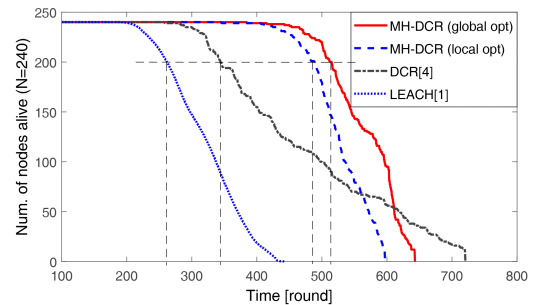


Fig. 2. Network lifespans in terms of the number of nodes alive ($N=240$)

the data with multi-hop schemes, whereas the nodes near the BS has much longer lifespan with single-hop schemes.

V. Conclusion

We have investigated into the effects of applying multi-hop to the deterministic cluster routing on energy efficiency. We consider the whole-path energy expense for multi-hop routing to achieve energy efficiency based on global optimization. The global optimization is achieved by iteration of updating the list of total energy expenses along the whole-path of the optimum multi-hop route from each CH node to the BS. Our multi-hop relaying improves existing deterministic cluster routing in terms of network lifespan, which is shown by simulations.

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