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Optimal Cluster Partitioning for Wireless Sensor Networks with Cooperative MISO Scheme

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***Abstract*—The paper discusses the optimal cluster partitioning for wireless sensor networks deployed in continuous areas. Both single-hop and multi-hop transmissions with cooperative Multi-Input Single-Output (MISO) scheme are considered for inter-cluster communications. The effects of cluster size in the energy consumption of intra-cluster communication and the amount of fused data are included in calculation. As a result, the dominant factors of the maximal network lifetimes are listed as: the cluster farthest from base station in single-hop transmission and the closest cluster in multi-hop transmission. In addition, the maximal network lifetimes of single-hop and multi-hop transmissions are compared and it is found that there exists a threshold of network size that determines which transmission is the better candidate.**

***Keywords*-cluster partitioning; cooperative MISO; single-hop; multi-hop; wireless sensor network**

I. INTRODUCTION

Wireless sensor networks (WSNs) have received much attention due to their great potential in many application domains, including industrial control, environment monitoring, and target tracking [1]. In some scenarios, a WSN is deployed in continuous areas and the information collected is necessary to transmit to a base station (BS) periodically, such as traffic surveillance on highway [2].

In general, a WSN consists of large numbers of spatially distributed sensor nodes. These nodes are usually powered by small batteries with limited energy, for which replacement or recharging is quite difficult if not impossible. That is, finite energy can only support the transmission of a finite amount of information. Hence, minimizing energy consumption and prolonging network lifetime are of great importance for the design of a WSN.

The clustering approach has proved to be one of the most effective mechanisms to improve energy efficiency in WSNs [3]. In cluster-based WSNs, many methods can be exploited to reduce energy consumption of inter-cluster transmission [4]. Cooperative Multi-Input Multi-Output (MIMO) and multi-hop are two typical schemes of them.

The original MIMO scheme based on antenna arrays can achieve spatial diversity in fading channels, which requires less transmission power than noncooperative Single-Input Single-Output (SISO) scheme [5]. However, it is difficult to apply MIMO scheme directly in WSNs because of the limited size of nodes which can only support a single antenna. Fortunately, if multiple nodes in a cluster could cooperate on data transmission and reception, a cooperative MIMO scheme can be constructed to improve communication performance [6].

As for a multi-hop scheme, the data of source clusters will be relayed by other clusters, while in a single-hop scheme the data will be transmitted to the BS directly. Therefore, shorter transmission distances of each hop will reduce the energy consumption of transmissions due to the characteristic of wireless signals that the path loss increases exponentially with transmission distance.

The authors of [6] and [7] have proposed some cooperative MIMO schemes for single-hop transmission in a clustered WSN and have analyzed their energy efficiency. It is shown that the number of cooperative nodes at both the transmission and reception sides should be selected with respect to the inter-cluster distance in order to minimize the total energy consumption. Although a cooperative MIMO scheme can improve the system performance in terms of energy conservation, it can not solve the energy imbalance of clusters caused by different distances to the BS in single-hop WSNs. Using a cooperative transmitting (Multi-Input Single-Output, MISO) scheme, Bai *et al.* [8] have investigated the unequal cluster partitioning in a continuous area WSN so as to balance energy consumptions among clusters and prolong lifetime of the network.

According to the result of [8], clusters closer to the BS should have smaller sizes and the farther ones have larger sizes in single-hop WSNs because more energy consumption for data transmitted to the BS is required with the increase of distances to the BS. However, energy consumption of intra-cluster communication (from nodes to the cluster head) is ignored in the model of [8]. In reality, such energy consumption will vary with the size of clusters. Clusters with larger sizes need more energy consumption for intra-cluster communication than those with smaller sizes. Furthermore, the amount of data after the data fusion process in the cluster

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head is assumed to be the same in each cluster, while it is more practical that clusters with larger sizes have more fused data to transmit.

Yuan *et al.* have extended the work in [6] and incorporated cooperative MIMO scheme with multi-hop networking [9]. Their results show that cooperative MIMO scheme can be also effective in energy saving for multi-hop WSNs. In spite of that, similar to previous single-hop networks, the energy imbalance problem still exists in a multi-hop WSN. For example, in a network with equal divided clusters, the clusters nearer to the BS may deplete their energy much faster than others because of higher traffic load. With consideration of the above problem, Mashreghi *et al.* [10] have developed an optimization model in a continuous area WSN and found the optimal parameters of the network, such as numbers of clusters and cooperative nodes, and sizes of clusters.

It is shown in [10] that for multi-hop networks, the optimal cluster partition is the same as for single-hop in [8]: clusters farther from the BS have larger sizes, but for different reason that clusters closer to the BS have to transmit more data and need shorter transmission distances. Nevertheless, the amount of fused data in each cluster has been considered also to be identical and independent of cluster sizes in [10]. And the energy consumption of intra-cluster communication never changed with cluster sizes despite that it was considered.

This paper expands and develops the works in [8] and [10]. The energy consumption of intra-cluster communication and the amount of fused data in each cluster are modeled as the functions of the cluster size. As a result, the cluster partitions which maximize the lifetime of network are presented in both single-hop and multi-hop transmissions using cooperative MISO scheme with the optimal number of cooperative transmitting nodes in each cluster. Accordingly, the dominant factors of the maximal network lifetimes are found. Furthermore, this paper completes the first attempt to compare the maximal lifetimes between single-hop and multi-hop transmissions by changing the dimension of optimal clustered network.

II. SYSTEM MODEL

Let us consider a linear network where the BS is located at the right end and the sensor nodes are uniformly deployed in a continuous area with node density ρ, as illustrated in Fig. 1. The length of the network D is much larger than the width W, and we divide the whole network into M rectangle clusters. As shown in Fig. 2, the position of the BS is $d_0 = 0$ and d_i is the distance between the left boundary of the ith cluster and the BS. Thus the area of the ith cluster ($i = 1, 2, \cdots, M$) is WD_i, where $D_i = d_i - d_{i-1}$. In each cluster, a special node served as a cluster head (CH) is placed at the center of its cluster. Since CHs have more energy supply than ordinary nodes because of their complicated tasks (e.g., data fusion, cluster management), the energy consumptions of CHs are not considered in our following discussion.

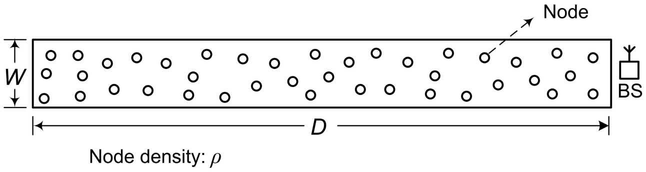

Figure 1. Network model

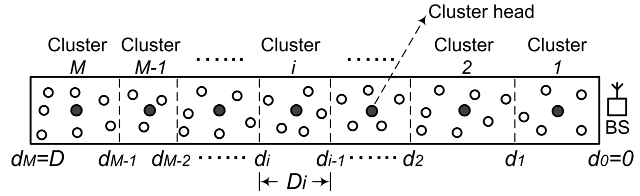

Figure 2. Cluster partitioning of the network

We assume that the network is periodical, i.e., each cluster needs to report their data to the BS per round. As far as each cluster is concerned, data transmission is composed of two parts: intra-cluster and inter-cluster communications. The intra-cluster communication takes place as follows. First, the nodes send their data to their CH. Then, the CH carries out data fusion, and combines them with the relaying data from other clusters if multi-hop transmission is used for inter-cluster communication. Finally, the CH selects cooperative transmitting nodes depending on the remaining energies of all nodes and broadcasts the data to them.

In the inter-cluster communication, cooperative transmitting nodes use a Space-Time Block Code (STBC) [11, 12] to encode the data, and transmit them simultaneously to the destination which is the BS in single-hop transmission or the CH of the next right cluster in multi-hop transmission. Since only CHs and the BS are arranged to receive the inter-cluster data, the model we consider here is a cooperative MISO system. If we also employ the cooperative strategy at the reception side, a cooperative MIMO system can be formed. Nevertheless, the cooperative MISO model can facilitate our analysis and be extended easily. It should be noted that CHs do not join data transmission of the cooperative MISO scheme because of their more but still limited energies.

III. ENERGY CONSUMPTION AND LIFETIME ANALYSIS

In this section we introduce the calculation of energy consumptions and give the definition of network lifetime. Then the problem of optimal cluster partitioning is presented. Let us assume that Binary Phase-Shift Keying (BPSK) is used as the modulation scheme and the network operates under a flat Rayleigh-fading channel for both intra-cluster and inter-cluster communications.

A. Energy consumptions of a node

1) For data transmission: According to the results of [6] and [13], when a node transmits data, the energy consumption per bit can be approximated as

$$\mathrm{E_T}(d, N) = \frac{Cd^k}{P_b^{1/N}} + \frac{P_{CT}}{R_b}, \tag{1}$$

where C is the product of some transmission constants, such as the thermal noise power spectral density (PSD) and the antenna gains, d is the transmission distance, k is the path loss factor, P_b is the required bit error ratio (BER), N ($N \geq 1$) is the number of cooperative transmitting nodes, P_{CT} is the power consumption of transmission circuits excluding the power amplifier, R_b is the transmission bit rate. In addition, $N = 1$ means noncooperative SISO transmission otherwise the node joins the cooperative MISO scheme.

2) For data reception: From [14], when a node receives data from its CH, the energy consumption per bit is given as

$$E_R = \frac{P_{CR}}{R_b}, \tag{2}$$

where P_{CR} is the power consumption of reception circuits.

B. Total energy consumptions of a cluster

Using $\mathrm{E_T}(d, N)$ and E_R defined above, let us calculate the total energy consumptions of all nodes in a cluster per round. Without loss of generality, we make the analysis in the ith cluster.

1) When all nodes transmit data to the CH: In the intra-cluster communication, every node needs to transmit its L bits of data to the CH by a noncooperative SISO scheme. In opposite to other papers (e.g., [7] and [10]), we use average path loss to calculate the energy consumptions. This makes the results more reasonable than assuming the distances from all nodes to the CH being identical. Therefore, the total energy consumption of all nodes in this step can be expressed as

$$\mathrm{E_{intra-i}}(d_i, d_{i-1}) = WD_i\rho L \mathrm{E_T}(\overline{d^k}_{intra-i}, 1), \tag{3}$$

where the average path loss of intra-cluster communication is denoted as

$$\overline{d^k}_{intra-i} = \frac{1}{WD_i}\int_{-\frac{W}{2}}^{\frac{W}{2}}\int_{-\frac{d_i-d_{i-1}}{2}}^{\frac{d_i-d_{i-1}}{2}} (u^2+v^2)^{\frac{k}{2}} du dv. \tag{4}$$

The calculation of the average path loss is based on our previous assumption that all nodes are uniformly deployed.

2) When cooperative transmitting nodes receive data from the CH: We assume the CH fuses all data from nodes by a ratio γ, this means the amount of fused data is directly proportional to the number of nodes or the size of cluster. Using (2), we can calculate the total energy consumptions when cooperative transmitting nodes receive data from the CH as follows:

- In single-hop transmission

$$\mathrm{E_{Rcni}}(d_i, d_{i-1}, N_i) = WD_i\rho L\gamma E_R N_i, \tag{5}$$

- In multi-hop transmission

$$\mathrm{E_{Rcni}}(d_{i-1}, N_i) = W(D - d_{i-1})\rho L\gamma E_R N_i, \tag{6}$$

where N_i is the number of cooperative transmitting nodes in the ith cluster.

3) When cooperative transmitting nodes transmit the data: Since the CH selects cooperative transmitting nodes in terms of the remaining energies of nodes to balance energy consumptions in the cluster, let us assume all nodes have equal probabilities to join the cooperative MISO scheme. Thus, we obtain the total energy consumptions when cooperative transmitting nodes transmit the data:

- In single-hop transmission

$$\mathrm{E_{inter-i}}(d_i, d_{i-1}, N_i) = WD_i\rho L\gamma \mathrm{E_T}(\overline{d^k}_{inter-i}, N_i)N_i, \tag{7}$$

where

$$\overline{d^k}_{inter-i} = \frac{1}{WD_i}\int_{-\frac{W}{2}}^{\frac{W}{2}}\int_{d_{i-1}}^{d_i} (u^2+v^2)^{\frac{k}{2}} du dv. \tag{8}$$

- In multi-hop transmission

$$\mathrm{E_{inter-i}}(d_i, d_{i-1}, d_{i-2}, N_i) = W(D - d_{i-1})\rho L\gamma \\ \mathrm{E_T}(\overline{d^k}_{inter-i}, N_i)N_i, \tag{9}$$

where

$$\overline{d^k}_{inter-i} = \begin{cases} \frac{1}{WD_1}\int_{-\frac{W}{2}}^{\frac{W}{2}}\int_0^{d_1}(u^2+v^2)^{\frac{k}{2}} du dv, \\ for\ i = 1; \\ \frac{1}{WD_i}\int_{-\frac{W}{2}}^{\frac{W}{2}}\int_{d_{i-1}-\frac{d_{i-1}+d_{i-2}}{2}}^{d_i-\frac{d_{i-1}+d_{i-2}}{2}}(u^2+v^2)^{\frac{k}{2}} du dv, \\ for\ 2 \leq i \leq M. \end{cases} \tag{10}$$

To sum up the above analysis, we achieve the total energy consumptions of the ith cluster per round, which is given by

$$\begin{aligned} &\mathrm{E_{round-i}}\,(d_i, d_{i-1}, d_{i-2}, N_i) \\ &\quad = \mathrm{E_{intra-i}}(d_i, d_{i-1}) + \mathrm{E_{Rcni}}(d_i, d_{i-1}, N_i) + \\ &\quad\quad \mathrm{E_{inter-i}}(d_i, d_{i-1}, d_{i-2}, N_i). \end{aligned} \tag{11}$$

C. The definition of network lifetime

If we assume that each node has J joules in its battery, then the lifetime of the ith cluster can be defined as the possible total transmission rounds, which can be calculated by

$$\mathrm{K_i}(d_i, d_{i-1}, d_{i-2}, N_i) = \frac{WD_i\rho J}{\mathrm{E_{round-i}}(d_i, d_{i-1}, d_{i-2}, N_i)}. \tag{12}$$

It is obvious that the network lifetime K is determined by the cluster which consumes all its energy firstly, i.e.,

$$K = \min_{1 \leq i \leq M} \mathrm{K_i}(d_i, d_{i-1}, d_{i-2}, N_i). \tag{13}$$

Table I
SYSTEM PARAMETERS

$D = 700$ m	$C = 4.05{\times}10^{-12}$
$\Delta = 50$ m	$k = 2$
$W = 10$ m	$P_b = 10^{-3}$
$\rho = 1/\mathrm{m}^2$	$R_b = 10$k bps
$\gamma = 0.5$	$P_{CT} = 98.2$ mW
$L = 100$ bit	$P_{CR} = 112.5$ mW
$J = 40$ joule	$N_i \in [1, 8]$

Table II
THE OPTIMAL CLUSTER PARTITION WHEN THE NUMBER OF CLUSTERS M=4 IN SINGLE-HOP TRANSMISSION

Cluster *i*	***1***	***2***	***3***	***4***
N_i	2	2	2	3
D_i (m)	300	200	150	50
K_i (round)	6139.0	6164.1	5774.9	5713.7

According to (13), we find that different cluster partitions and numbers of cooperative transmitting nodes may result in different network lifetimes. For the sake of maximizing network lifetime, it is necessary to investigate the optimal cluster partitions and cooperative MISO schemes, which will be clarified below.

IV. SIMULATIONS AND NUMERICAL RESULTS

This section illustrates the optimal cluster partitioning by numerical examples and summarize the relevant regularities. The system parameters used in the simulations are shown in Table I. Minimum step size or resolution of the cluster length D_i is set to be Δ, which is a divisor of D. Accordingly, the maximal number of clusters is D/Δ $(= 14)$. Although such assumption will lead to approximate results, it does not affect our conclusions. In the simulations, for every number of clusters, we first consider all possible cluster partitions, then find the maximal network lifetimes based on (13).

A. Single-hop transmission

In single-hop transmission, the maximal network lifetimes with different numbers of clusters are plotted in Fig. 3, where we see that the maximal network lifetime increases with the number of clusters and saturates at $M = 4$.

Table II shows the optimal numbers of cooperative transmitting nodes, optimal cluster sizes and corresponding cluster lifetimes with $M = 4$. From this table, it is observed that the clusters farther from the BS need larger numbers of cooperative transmitting nodes N_i, which is in accord with the results of previous works [6, 7]. But more important is that such farther clusters have smaller sizes, which is entirely different from the former results in [8]. This can be explained as follows: In single-hop transmission, the increase of the cluster size reduces the possibility of nodes joining the inter-cluster communication, but at the same time it increases the amount of fused data to be transmitted. Consequently, the farther clusters can not reduce energy consumptions of inter-cluster communications by increasing their sizes. On the contrary, they will benefit from smaller sizes which can save energy consumptions of intra-cluster communications.

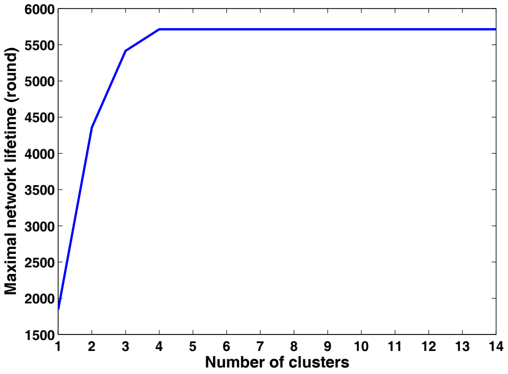

Figure 3. The maximal network lifetimes with different numbers of clusters in single-hop transmission

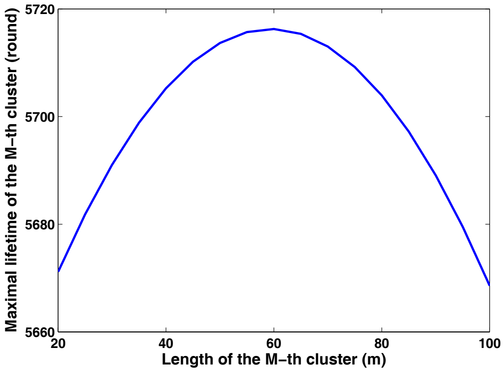

Figure 4. The maximal lifetimes of the Mth cluster in single-hop transmission

From Table II, we can also judge that the Mth cluster determines the maximal network lifetime in single-hop transmission. In Fig. 3, the maximal network lifetime remains unchanged when the number of clusters $M \geq 4$. This is because of the limit in the minimum cluster size. When $M \geq 4$, the Mth cluster always has a length $\Delta = 50$ meters in the optimal cluster partitions.

Since the left boundary of the Mth cluster is fixed at D, reducing its size means decreasing the energy consumption of intra-cluster communication, while increasing its average distance from the BS. That brings up a trade-off and causes the result shown in Fig. 4, in which a smaller resolution $\Delta = 5$ meters is used to find the maximal lifetime of the Mth cluster. From this figure, we find that there exists a maximal lifetime of the Mth cluster at $D_M = 60$ meters. This maximal lifetime of the cluster is also the possible maximal network lifetime in single-hop transmission.

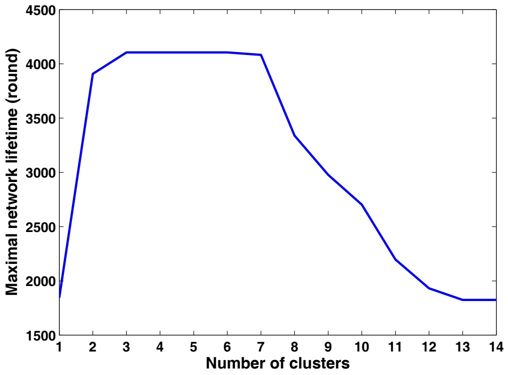

Figure 5. The maximal network lifetimes with different numbers of clusters in multi-hop transmission

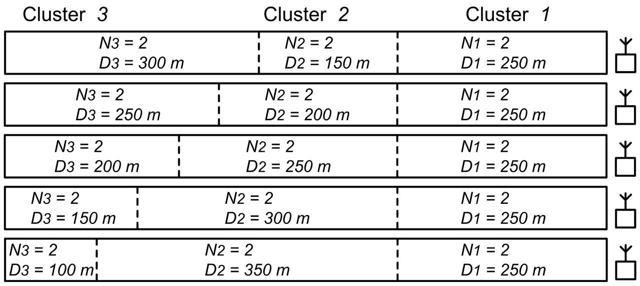

Figure 6. The five optimal cluster partitions when the number of clusters M=3 in multi-hop transmission

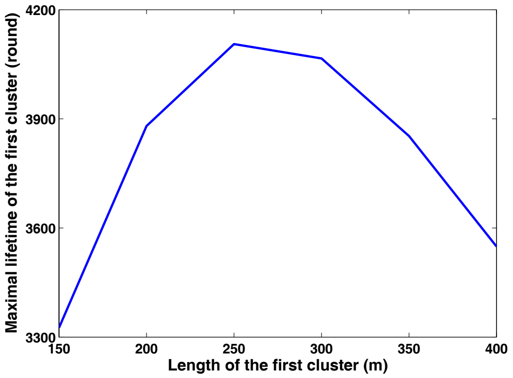

Figure 7. The maximal lifetimes of the first cluster in multi-hop transmission

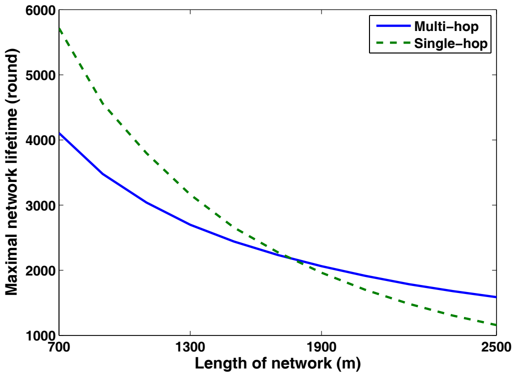

Figure 8. The maximal network lifetimes of single-hop and multi-hop transmissions at different lengths of network

B. Multi-hop transmission

Fig. 5 shows the maximal network lifetimes with different numbers of clusters in multi-hop transmission. When the number of clusters $M = 3$, we can get the maximal network lifetime, and the corresponding five sets of optimal cluster partitions are presented in Fig. 6.

It is interesting that among these optimal partitions, the size of the first cluster is fixed while those of other clusters can change. This implies that the maximal network lifetime in multi-hop transmission is determined by the first cluster. In fact, the simulation result of the maximal lifetime of the first cluster in Fig. 7 shows the 250 meters is exactly the optimal length of this cluster. In other words, there exists a preferred size of the first cluster so that the network can achieve its maximal lifetime which is equal to that of this cluster.

As can be seen from Fig. 7, too large or small size of the first cluster reduces its maximal lifetime in multi-hop transmission. This comes from the trade-off of two different factors. Smaller size of the cluster makes its energy consumptions of intra- and inter-cluster communications smaller. On the other hand, larger size of the cluster with larger number of nodes provides smaller chance for each node to be involved in the inter-cluster communication, and this causes smaller power consumption of each node.

C. Single-hop vs. Multi-hop

In the above two subsections, we obtain the optimal cluster partitions in both single-hop and the multi-hop transmissions when the length of network $D = 700$ meters and find the dominant factors of maximal network lifetimes.

In accordance with the previous analysis, let us evaluate the maximal network lifetimes of single-hop and multi-hop transmissions at different lengths of network and compare their performances. The simulation results plotted in Fig. 8 show that there is a threshold of the comparison. If the length of network is smaller than the threshold, single-hop transmission will outperform multi-hop, otherwise multi-hop will be better. In other words, multi-hop transmission is appropriate for large-scale networks while single-hop wins in small-scale networks.

V. CONCLUSION

In this paper, we have investigated the optimal cluster partitioning for single-hop and multi-hop transmissions with cooperative MISO scheme in a continuous area WSN. Compared with existing works in this field, this paper has considered both the energy consumption of intra-cluster communication and the amount of fused data in every cluster as functions of the cluster size. Furthermore, average path loss has been employed to calculate energy consumptions for the exact results.

By numerical simulations, we have obtained the optimal numbers and sizes of clusters, the optimal numbers of cooperative transmitting nodes in each cluster for the maximal network lifetimes. Consequently, we have found the dominant factors of the maximal network lifetimes, which are different from other related works. In single-hop transmission, the optimal cluster partition indicates that clusters farther from base station should be assigned with smaller sizes and the farthest cluster determines the maximal network lifetime. As for multi-hop transmission, the cluster closest to base station is vital and there exists the preferred size of this cluster which lead the network to achieve its maximal lifetime.

Additionally, we have made the first attempt to compare the maximal lifetimes of single-hop and multi-hop transmissions in the clustered network at its different lengths. It is found that multi-hop transmission outperforms single-hop when the length of network is large enough, otherwise single-hop transmission is the better candidate.

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