LETTER

Optimal Ratio of Direct/Multi-Hop Forwarding for Network Lifetime Maximization in Wireless Sensor Networks

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SUMMARY In this letter, we discuss a forwarding method for maximizing network lifetime, which combines multi-hop forwarding and direct forwarding with a direct/multi-hop forwarding ratio of each sensor node. The direct forwarding ratio refers to the forwarding amount ratio of sensor nodes’ own data directly towards a sink node in one packet/instance data generation rate. We tackle an optimization problem to determine the direct forwarding ratio of each sensor node, maximizing network lifetime, as well as nearly guaranteeing energy consumption balancing characteristics. The optimization problem is tackled through the Lagrange multiplier approach. We found that the direct forwarding ratio is overall inversely proportional to the increase of node index in \( h < i \leq N \) case. Finally, we compare energy consumption and network lifetime of the proposed forwarding method with other existing forwarding methods. The numerical results show that the proposed forwarding method balances energy consumption in most of the sensor nodes, comparing with other existing forwarding methods, such as multi-hop forwarding and direct forwarding. The proposed forwarding method also maximizes network lifetime.

key words: multi-hop forwarding, wireless sensor networks, direct forwarding ratio, energy consumption, network lifetime

1. Introduction

Energy consumption management is a crucial task in Wireless Sensor Networks (WSNs) design, and a major part of the energy consumption components for efficient WSNs design is data transmission of sensor nodes. In WSNs, sensor nodes further from the sink node prefer to use Multi-hop Forwarding (MhF) for energy efficiency. Alternatively, sensor nodes near the sink node prefer to use Direct Forwarding (DrtF) for relieving the load of forwarding from the outer sensor nodes. In [1], urgent data has been researched, and the authors discussed a landslide disaster monitoring system for observing natural disasters. The Wireless Sensor and Actor Networks (WSANs) are presented in [2], and sensor nodes collaborate with actor nodes that form WSANs in the predicted forest fire area. Energy balanced propagation for WSNs has been analyzed to prolong network lifetime in [3].

We argue that determining the direct/multi-hop forwarding ratio of each sensor node can be an effective method when combining multi-hop forwarding and direct forwarding, which maximizes network lifetime. In this letter, we refer to our forwarding method as a direct/multi-hop forwarding ratio based Mh-Drt forwarding (Mh-DrtF). The direct forwarding ratio of each sensor node refers to the forwarding amount ratio of its own data directly towards a sink node in one packet/instance data generation rate. We consider how an optimal direct forwarding ratio can be determined in combination of multi-hop forwarding and direct forwarding, while maximizing network lifetime. The optimal direct forwarding ratio can be determined by an optimization problem. We tackle the optimization problem of \( h \) unit multi-hop case direct/multi-hop forwarding ratio based Mh-Drt forwarding situation. To get the solutions for the optimization problem, we utilize the Lagrange multiplier approach for finding the optimal direct forwarding ratio of each sensor node. Our solutions in the given condition reveal that the direct forwarding ratio is overall inversely proportional to the increase of node index in \( h < i \leq N \) case. We compare energy consumption and network lifetime of the proposed forwarding method with other forwarding methods (e.g. multi-hop forwarding, direct forwarding, and various constant direct forwarding ratio based forwarding methods). The information that needs for each node in [6] is “distance to the sink node” and “distance to the furthest node.” In contrast to [6], sensor nodes in the proposed forwarding method only need to know the “\( h \) unit neighbor node index towards a sink node” and the “direct forwarding ratio of \( h \) unit neighbor node index towards a sink node” if the electronics energy value and \( h \) value are given.

This letter is organized as follows. We introduce direct/multi-hop forwarding ratio based Mh-Drt forwarding method in Sect. 2. In Sect. 3, our optimization problem is discussed. Afterwards, the numerical results are shown in Sect. 4. Finally, we complete this letter with a conclusion in Sect. 5.

2. Direct/Multi-Hop Forwarding Ratio Based Mh-Drt Forwarding Method

2.1 System Description of the Proposed Forwarding Method

The sensor nodes are placed on a line regularly from the 1st node index through the \( N \)th node index in a linear model manner. Each of the sensor nodes from the 1st node index through the \( N \)th node index constantly reports data with one packet/instance data generation rate towards a sink node direction until network lifetime ends. An instance refers to the execution period for one forwarding task of each sensor node. The forwarding task is started from the \( N \)th node in-
dex towards a sink node and ended with the 1st node index. Additionally, each sensor node has the same amount of initial energy. Energy consumption of each sensor node is only considered as forwarding energy consumption, in a similar manner to [6]. In Fig. 1, we depict the proposed forwarding method for the \( i \)th sensor node case, where the sensor nodes are located in a linear manner.

Table 1 describes notations for our optimization problem, which is referenced from [4]–[6], and some of the notations have predetermined values.

| \( i \) | sensor node index (1 \( \leq \) i \( \leq \) N, where i is a positive integer) |
| \( N \) | total number of sensor nodes (= 100) |
| \( e_{\text{on}} \) | electronics energy (= 50 unit) |
| \( \eta \) | transmission amplifier coefficient (= 1 unit) |
| \( d \) | distance between the \( i \)th node and the \((i+\ell)\)th node (= 1 unit) |
| \( \alpha \) | path loss component (= 2) |
| \( e_{\text{i}} \) | energy consumption of the \( i \)th sensor node (= \( \gamma e_{\text{elec}} + (i + h)^2 \)) |
| \( e_{\text{col}} \) | initial energy of each sensor node (= 10\(^3\) unit) |
| \( h \) | hop distance of multi-hop (1 \( \leq \) h \( \leq \) N) |
| \( \gamma_i \) | direct forwarding ratio of the \( i \)th sensor node (0 \( \leq \gamma_i \leq \) 1) |
| \( 1-\gamma_i \) | multi-hop forwarding ratio of the \( i \)th sensor node (0 \( \leq \gamma_i \leq \) 1) |

2.2 Features of the Direct/Multi-Hop Forwarding Ratio Based Mh-Drt Forwarding Method

The direct/multi-hop forwarding ratio based Mh-Drt forwarding is a forwarding method that combines multi-hop forwarding and direct forwarding with a direct/multi-hop forwarding ratio. It is classified by a hop distance \( h \) of the multi-hop forwarding. In the direct/multi-hop forwarding ratio based Mh-Drt forwarding, sensor nodes from the 1st node index through the \( h \)th node index (i.e. \( 1 \leq i \leq h \)) only forward their data with the direct forwarding method.

![Fig. 1 System description of the proposed forwarding method for the \( i \)th sensor node case, which is referenced from [6].](image)

3. Optimization Problem

**Objective function**

- \( \min(e_i), \) where \( h < i \leq N \) case

**Constraints**

\[
\begin{align*}
\gamma_i(e_{\text{elec}} + i^2) + (1 - \gamma_i)(e_{\text{elec}} + h^2) \\
+ (e_{\text{elec}} + h^2) \sum_{j=0}^{\lfloor \frac{h}{2} \rfloor - 1} (1 - \gamma_{j+i-jh}) \\
= e_i, & \text{ } h < i \leq N \text{ case} \\
0 \leq \gamma_i \leq 1
\end{align*}
\]

The optimization problem of this letter is minimizing the forwarding energy consumption \( e_i \) in \( h < i \leq N \) case. The network lifetime would be increased by the forwarding energy minimization in WSNs. There are two constraints for the optimization problem. The first constraint is the forwarding energy consumption between the \( i \)th node and the \((i + h)\)th node. In addition, the forwarding energy consumption of the \( i \)th node is equal to the sum of the following: direct forwarding amount of the \( i \)th node’s own forwarding (indicated as \( \widehat{g} \) in Fig. 1), \( h \) unit multi-hop forwarding amount of the \( i \)th node’s own forwarding (indicated as \( \overline{g} \) in Fig. 1), and \( h \) unit multi-hop forwarding amount from the \((i + h)\)th node (indicated as \( g^* \) in Fig. 1). The function \( \lfloor \cdot \rfloor \) is referenced from [6], and it is used for selection of the outer sensor nodes for \( h \) unit multi-hop forwarding. As \( 1 \leq i \leq h \) case nodes forward data only with the direct forwarding method (i.e. \( \gamma_1 = 1 \) if \( 1 \leq i \leq h \)), only the \( h < i \leq N \) case is considered in this constraint. The second constraint is the direct forwarding ratio. We get the solutions of the optimization problem through the Lagrange multiplier approach for a single constraint case. From the Eq. (1) through the Eq. (5), we only consider \( h < i \leq N \) case.

\[
f = \gamma_i(e_{\text{elec}} + i^2) + (1 - \gamma_i)(e_{\text{elec}} + h^2) \\
+ (e_{\text{elec}} + h^2) \sum_{j=0}^{\lfloor \frac{h}{2} \rfloor - 1} (1 - \gamma_{j+i-jh}) \\
- \gamma_{i+h} [e_{\text{elec}} + (i + h)^2] \\
- (1 - \gamma_{i+h})(e_{\text{elec}} + h^2) \\
- (e_{\text{elec}} + h^2) \\
\times \sum_{k=0}^{\lfloor \frac{h}{2} \rfloor - 1} (1 - \gamma_{k+i-hk}) \\
= \gamma_i(l^2 - h^2) + e_{\text{elec}} + h^2
\]
The Lagrange function in Eq. (3) can be solved by the partial derivatives of the direct forwarding ratio in Eq. (4) and the Lagrange multiplier in Eq. (5).

\[
F = \gamma_i(e_{elec} + i^2) + (1 - \gamma_i)(e_{elec} + h^2)
+ \gamma_i(e_{elec} + h^2) \sum_{j=0}^{[\frac{n}{h}] - 1} \left(1 - \gamma_j [n \gamma_j]_{h+i-jh}\right)
+ \lambda \left[\gamma_i(i^2 - h^2) + e_{elec} + h^2\right]
- \gamma_i [h + h^2 - h^2] - (e_{elec} + h^2)
+ \gamma_i(e_{elec} + h^2) \sum_{j=0}^{[\frac{n}{h}] - 1} \left(1 - \gamma_j [n \gamma_j]_{h+i-jh}\right)
- \sum_{k=0}^{[\frac{n}{h}] - 1} \left(1 - \gamma_j [n \gamma_j]_{h+i-jh-k}\right)
\]

\[
\frac{\partial F}{\partial \gamma_i} = e_{elec} + i^2 - (e_{elec} + h^2) + \lambda (i^2 - h^2) = 0
\]

\[
\frac{\partial F}{\partial \lambda} = \gamma_i(i^2 - h^2) + e_{elec} + h^2
- \gamma_i [h + h^2 - h^2] - (e_{elec} + h^2)
+ \gamma_i(e_{elec} + h^2) \sum_{j=0}^{[\frac{n}{h}] - 1} \left(1 - \gamma_j [n \gamma_j]_{h+i-jh}\right)
- \sum_{k=0}^{[\frac{n}{h}] - 1} \left(1 - \gamma_j [n \gamma_j]_{h+i-jh-k}\right) = 0
\]

As a result, in \(1 \leq i \leq h\) case, sensor nodes transmit data with direct forwarding as follows.

\[
\gamma_i = 1
\]

Also, in \(h < i \leq N\) case, sensor nodes transmit their own data with a combination of multi-hop forwarding and direct forwarding, using the direct forwarding ratio as follows.

\[
\gamma_{i+h} = \frac{\gamma_i(i^2 - h^2) + (e_{elec} + h^2)}{e_{elec} + (i + h)^2}
\]

As the \(h\) value is \(1 \leq h \leq N\), the values from \(\gamma_1\) through \(\gamma_h\) are initially assigned as 1, and then the values from \(\gamma_{h+1}\) through \(\gamma_N\) are determined with a consecutive order by Eq. (7). For instance, \(\gamma_{h+1}\) is determined by \(\gamma_1\). Therefore, the direct/multi-hop forwarding ratio based Mh-Drt forwarding is related to the \(i\) factor if \(e_{elec}\) and \(h\) are given.

4. Numerical Results

In Sect. 4, we provide the numerical results of energy consumption and network lifetime comparisons among the various forwarding methods in given condition.

In Fig. 2, the \(h = 1\) case direct/multi-hop forwarding ratio based Mh-Drt forwarding method (i.e. Mh-DrtF (\(h = 1\))) is compared with other forwarding methods. Among the forwarding methods, Mh-DrtF (\(r = 0.1\)) and Mh-DrtF (\(r = 0.5\)) refer to the \(h = 1\) case Mh-Drt forwarding methods, which use an identical value of direct forwarding ratio, such as \(r = 0.1\) and \(r = 0.5\), in each sensor node, respectively. Even though other forwarding methods induce an imbalanced energy consumption property, the proposed forwarding method (i.e. Mh-DrtF (\(h = 1\))) shows energy balancing characteristics in nearly all of the sensor nodes. Also, the proposed forwarding method (i.e. Mh-DrtF (\(h = 1\))) reduces energy consumption of sensor nodes near the sink node in MhF and energy consumption of sensor nodes further from the sink node in DrtF.

Then, Fig. 3 shows network lifetime comparison results of the various forwarding methods. In this letter, we define network lifetime as the time when the first sensor node exhausts its energy in it. In Fig. 3, the network lifetime of Mh-DrtF (\(h = 1\)) presents the highest rank among the various forwarding methods, and DrtF depicts the lowest rank among the various forwarding methods.

Figure 4 describes the energy consumption for one packet/instance in various \(h\) unit multi-hop cases (e.g. \(h = 1, 4, 7, 11, 15, 20\)) direct/multi-hop forwarding ratio based Mh-Drt forwarding. Referenced from [6], the optimum transmission range \(h\) can be estimated as follows.

\[
h \approx \max \left(1, \left(\frac{e_{elec}}{\alpha - 1}\right)^{\frac{1}{2}}\right)
\]
In the proposed forwarding method condition, we can obtain the optimal hop distance \( h \) as 7 from Eq. (8). In addition, Fig. 4 reveals that the \( h = 7 \) case produces almost the least energy consumption, and this reflects the correctness of the optimal hop distance \( h \) value for the proposed forwarding method. The various \( h \) unit multi-hop cases direct/multi-hop forwarding ratio based Mh-Drt forwarding, except the \( h = 1 \) case, do not have overall energy balanced property. The reason is that the sensor nodes transmit their data only with the direct forwarding method in \( 1 \leq i \leq h \) case, and this causes energy imbalanced property in \( 1 \leq i \leq h \) case. Moreover, Fig. 4 also shows that energy consumption is not exactly balanced as the \( h \) value increases.

5. Conclusion

In this letter, we got the solutions of an optimization problem for network lifetime maximization in linear model based WSNs by determining a ratio of multi-hop forwarding and direct forwarding. We determined the optimal ratio of direct/multi-hop forwarding through the Lagrange multiplier approach. The optimization problem presents that the direct forwarding ratio is overall inversely proportional to the increase of node index in \( h < i \leq N \) case, which implies that the direct forwarding ratio values get overall lower as the sensor nodes are placed further from the sink node. Comparing energy consumption and network lifetime with other existing forwarding methods (e.g. multi-hop forwarding method, direct forwarding method, and various constant direct forwarding ratio based Mh-Drt forwarding methods), our direct/multi-hop forwarding ratio based Mh-Drt forwarding method can maximize the network lifetime in most of the sensor nodes, as well as shows energy consumption with nearly balancing characteristics.

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