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MDC 기반 데이터 수집 네트워크에서의 패킷지연 최소화

Minimization of Packet Delay in a Mobile Data Collector (MDC)-based Data Gathering Network

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요 약 본 논문에서는 데이터수집을 위한 MDC(mobile data collector) 기반의 무선센서네트워크를 고려한다. 이러한 네트워크에서는 MDC들이 이동하며 주위환경으로부터 데이터를 수집한 후 싱크노드에게 전달한다. 단일 MDC를 사용하는 기존 방식에서는 높은 데이터 수집 지연 문제가 발생한다. 복수의 MDC를 사용하는 일부 기존 방안에서는 네트워크 수명최대화에 초점을 두고 데이터 전달 지연에 대한 고려는 하지 않았다. 기존 방안의 이러한 제약을 극복하기 위하여 본 논문에서는 MDC의 개수가 주어진 상황에서 패킷지연을 최소화하는 문제와, 최대 허용 패킷 지연이 주어진 상황에서 필요한 MDC의 수를 최소화 하는 문제를 고려한다. 이를 위해서 두 개의 최적화 문제가 구성되었으며 MDC들의 이동거리와 이동시간 추정 모델을 개발하였다. Interior-point 알고리즘을 이용하여 최적화 문제에 대한 해를 구했으며, 제안된 방안을 검증하기 위한 수치결과와 분석을 제시하였다.

Abstract In this paper, we study mobile data collector (MDC) based data-gathering schemes in wireless sensor networks. In Such networks, MDCs are used to collect data from the environment and transfer them to the sink. The majority of existing data-gathering schemes suffer from high data-gathering latency because they use only a single MDC. Although some schemes use multiple MDCs, they focus on maximizing network lifetime rather than minimizing packet delay. In order to address the limitations of existing schemes, this paper focuses on minimizing packet delay for given number of MDCs and minimizing the number of MDCs for a given delay bound of packets. To achieve the minimum packet delay and minimum number of MDCs, two optimization problems are formulated, and traveling distance and traveling time of MDCs are estimated. The interior-point algorithm is used to obtain the optimal solution for each optimization problem. Numerical results and analysis are presented to validate the proposed method.

Key Words : Mobile data collectors, Mobile Sensor Networks, Packet Delay bound, Optimization problems.

Ⅰ. Introduction

Wireless sensor networks (WSNs) that consist of a large number of stationary sensors have been widely used in various applications, such as intruder detection, health monitoring and environment sensing [1-3]. In WSNs, data gathering from distributed sensors that are deployed over a large area is the most important task.

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Data gathering in WSNs has traditionally been performed via multi-hop data forwarding to the sink [4]. In such a network, a node might spend most of its power relaying other nodes' packets. Over time, as nodes die, the network tends to become disconnected, leading to loss of coverage and connectivity.

One way to solve this problem is to introduce mobility in WSNs [5-12]. In such schemes, mobile data collectors (MDCs) are used to collect the data from sensors deployed over the area and bring the data to the sink. By using MDCs, data gathering can be possible in a sparse or disconnected network because MDCs can travel and directly collect data from the sensors.

The existing data-gathering schemes suffer from high data-gathering latency because they use only a single MDC [5-8]. Although some schemes use multiple MDCs,they cannot estimate data-gathering latency due to random mobility [9-11], or focus on maximizing network lifetime rather than minimizing packet delay [12].

Therefore, in order to address these problems, we propose a new model for mobile data collection to minimize packet delay for a given number of MDCs and to also determine the minimum number of MDCs for a given delay bound of packets. In our proposed model, the entire circular area is divided into a number of levels based on the number of MDCs. Every level needs to have an equal number of MDCs. The sink is placed at the center of the area. The MDC of the first level starts its tour from the sink, collects data from this area and deposits the collected data at the sink. The MDCs of other levels start their tours and return to the same point after collecting data from their areas. The tours are continued periodically.

In this paper, in order to achieve minimum packet delay using the given MDCs, and to obtain the minimum number of MDCs for a given delay bound of packets, two optimization problems are formulated. After that, the traveling distance of every level and the traveling time of MDCs are estimated. To solve the first optimization problem, the traveling time of MDCs are estimated as a function of the width of the levels and the arc angle of a cone. To solve the second optimization problem, the traveling time of each MDC is also estimated as a function of the width of the levels and the number of MDCs. Then, the interior-point algorithm with different initial values is used to obtain the optimal solutions. Numerical results and analysis are presented to validate the proposed method.

The rest of the paper is organized as follows, Section II describes the system model and problem definition. Section III and Section IV present optimization formulations to find the solution and the numerical study, respectively. Finally, Section V concludes the paper.

II. System Model and Problem Definition

In this section, we describe the network model and the problem definition in detail. We consider a circular area with radius d, where the sink is placed at the center of the area. The entire circular area is divided into multiple levels based on the number of MDCs. Then, multiple cones are created in the entire area. The side of the cone is known as the slant. In this paper, K denotes the total number of levels in the area, and w_i denotes the width of level i $(1 \le i \le K)$. Here, every level has an equal number of MDCs. Let N denote the total number of MDCs. In this paper, we denote v and R as the speed of MDC and sensing range, respectively. Let α denote the arc angle of a cone where $\alpha = \frac{2\pi K}{N}$. Each level has a number of stripes, which follow MDCs as their trajectories. 2R is the distance between two adjacent stripes. The first-level MDCs start moving from the position of the sink, collect data from the area of the first level, and deposit the collected data at the sink. The paths of other MDCs begin and end at the same point of the stripes of their levels. The MDCs follow the slant and stripes of their level as their trajectories for collecting data from the area. After collecting data, the MDCs follow only the slant of their level to return to their initial position.

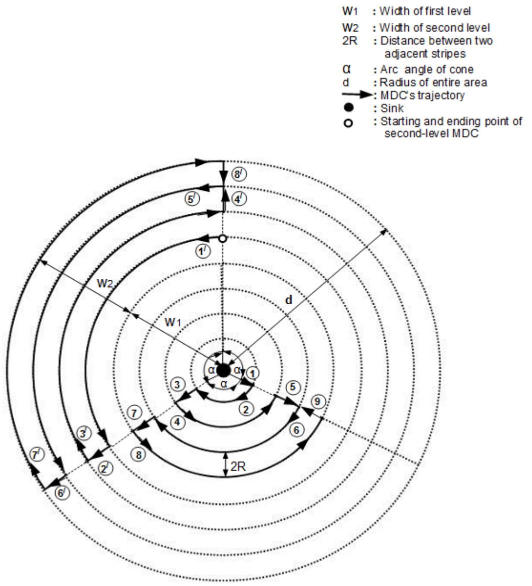

그림 1. 첫 번째와 두 번째 레벨에서의 MDC 이동 경로 예
Fig. 1. An example of the first- and second-level MDC tour

Fig. 1 illustrates the first- and second-level MDC tours. In Fig. 1, the sink is placed at the center of the area. Assume there are six MDCs (i.e.,N = 6) and every level has three MDCs. As a result, the entire area is divided into two levels (i.e.,K = 2) and three cones are created in the entire area. Therefore, the arc angle of each cone is $\alpha = \frac{2\pi}{3}$.w_1 and w_2 represent the widths of the first and second levels. In both levels, there are multiple stripes, which MDCs follow as their trajectories. After collecting data, the MDCs return to their initial position, and the tour is repeated periodically. The trajectories of the first- and second-level MDC are marked in Fig. 1 with 1 to 9 and 1′ to 8′, respectively.

The work in this paper focuses on achieving the minimum packet delay for a given number of MDCs, and determining the least number of MDCs for a given delay bound of packets. Therefore, in this paper, two optimization problems are defined and formulated.

Problem 1. Minimization of packet delay given the number of MDCs (MIN-PD)

In MDC-based data gathering schemes, data delivery relies on the physical movements of MDCs. In such schemes, minimum packet delay can be achieved by minimizing traveling time of the MDCs.Therefore, MIN-PD problem can be regarded as one to minimize traveling time for the given number of MDCs. Let T_i $(i = 1,...,K)$ denote the traveling time of MDCs of level i, and T_i can be expressed as a function of the width of the level and the arc angle of a cone. We also defined τ as an optimization variable that represents the traveling time of the MDCs. Recall that w_i represents the width of level i $(1 \le i \le K)$, which is another optimization variable, and α is the arc angle of a cone.

Then, the MIN-PD problem can be formulated as follows. Minimize the traveling time of MDCs, τ, for a given number of MDCs and using the given number of MDCs, the traveling time required at level i $(1 \le i \le K)$, T_i, must be equal or less than τ. That is,

$$\text{minimize } \tau \quad (1)$$

$$\text{subject to } T_i(w,\alpha) \le \tau, \qquad i = 1,...,K \quad (2)$$

$$\sum_{i=1}^{K} w_i = d \quad (3)$$

Here, Eq. 3 states that the sum of the widths of all levels is equal to the radius of the entire area, d.

Problem 2. Minimization of the number of MDCs given the packet delay bound (MIN-MDC)

In some applications of MDC-based data gathering schemes, packets may be required to reach the sink within a certain delay limitation. Therefore, in the MIN-MDC problem, we focus on minimizing the number of MDCs when the packet delay bound is given. Let F_i $(i=1,...,K)$ denote the traveling time of MDCs of each level, and $F_i$can be expressed as a function of the width of the level and the total number of MDCs. t denotes the required value of packet delay. Here, the optimization variable is N (i.e., the total number of MDCs) and w_i $(i=1,...,K)$ is another optimization variable. Then, MIN-MDC problem is to minimize the number of MDCs, given the packet delay bound, where the traveling time of MDCs at level i $(1 \le i \le K)$ satisfies the required packet delay bound, t, which is formulated as follows:

$$\text{minimize } N \tag{4}$$

$$\text{subject to } F_i(w,N) \le t, \quad i=1,...,K \tag{5}$$

$$\sum_{i=1}^{K} w_i = d \tag{6}$$

Note that the speed of the MDCs is given, and every level has an equal number of MDCs.

III. Finding Solutions

In order to solve both problems, we need to estimate the traveling time of MDCs. For MIN-PD, since the number of MDCs is given, traveling time of MDCs is a function of the width of the level and the arc angle of a cone. For MIN-MDC, traveling time of MDCs is a function of the width of the level and the number of MDCs. Therefore, we first estimate the traveling distance for every level. Then, we estimate the traveling time of MDCs based on the traveling distance of every level and the speed of MDCs.

In this section, we first describe estimation of the traveling distance of MDCs. Then, we present optimization formulations to find the solutions for MIN-PD problem and MIN-MDC problem.

1. Estimation of Traveling Distance of MDCs

In this subsection, we describe the estimation of traveling distance of MDCs for level i, where $i=1,...,K$. Let L_1 and L_i $(i=2,...,K)$ denote the traveling distance of the first level and level i, respectively. Recall that the path of the MDC consists of the slant and stripes of this level. MDCs follow the slant and stripes of the level as their trajectories for collecting data from the area. When MDCs return to the initial position, they follow only a slant of the level. Note that the slant height is equal to the width of the level.

Recall that w_1 and w_i represent the width of the first level and level i $(2 \le i \le K)$, respectively. Note that $s_m\,(m=1,...,\frac{w_1}{2R})$ and $s_n\,(n=\frac{w_1}{2R}+1,...,\frac{w_1+w_i}{2R})$ are the lengths of the stripes in the first level and level i, respectively. The distance between two adjacent stripes is 2R. Note that the entire area is divided into K levels, so the radius of the entire area is $d=\sum_{i=1}^{K} w_i$. Using $s_m\,(m=1,...,\frac{w_1}{2R})$ and w_1, the traveling distance of the first level, L_1, can be calculated as

$$L_1 = 2w_1 + (s_1 + s_2 + ... + s_{(\frac{w_1}{2R})}) \tag{7}$$

By substituting $s_m = 2\alpha mR$ where $m=1,...,\frac{w_1}{2R}$ into Eq.7, we obtain

$$L_1 = 2w_1 + 2\alpha R(1+2+...+\frac{w_1}{2R})$$
$$= \frac{\alpha w^{2_1}}{2R} + (\alpha+4)w_1 \tag{8}$$

In a similar way, using$s_n\,(n=\frac{w_1}{2R}+1,...,\frac{w_1+w_i}{2R})$ and w_i $(2 \le i \le K)$, the traveling distance of level i $(2 \le i \le K)$, L_i, can be calculated as

$$L_i = 2(w_i - 2R) + (s_{(\frac{w_1}{2R}+1)} + s_{(\frac{w_1}{2R}+2)} + ... + s_{(\frac{w_1}{2R}+\frac{w_i}{2R})}) \tag{9}$$

Here, the MDC starts its tour from the $(\frac{w_1}{2R}+1)$th stripe and ends the tour at the same point. Therefore, we subtract 2R from w_i. By substituting $s_n = 2\alpha nR$

where $n=\frac{w_1}{2R}+1,...,\frac{w_1+w_i}{2R}$ into Eq. 9, we get

$$L_i=2(w_i-2R)+2\alpha R((\frac{w_1}{2R}+1)+(\frac{w_1}{2R}+2)+...+(\frac{w_1}{2R}+\frac{w_i}{2R}))$$

$$=\frac{\alpha w_i^2}{2R}+(\frac{\alpha}{R}(\sum_{j=1}^{i-1}w_j)+\alpha+4)w_i-8R \quad (10)$$

2. Finding the Solution for MIN-PD problem

In this section, we present optimization formulations to find the solution for MIN-PD problem. Recall that T_i $(i=1,...,K)$ represents the traveling time of MDCs, which is a function of w and α. MDCs move at speed v. Using L_i $(i=1,...,K)$ and v, the value of T_i $(i=1,...,K)$ can be calculated as

$$T_1(w,\alpha)=\frac{L_1}{v}=\frac{\alpha w_1^2}{2vR}+(\alpha+4)\frac{w_1}{v} \quad (11)$$

$$T_i(w,\alpha)=\frac{L_i}{v}=\frac{\alpha w_i^2}{2vR}+(\frac{\alpha}{R}(\sum_{j=1}^{i-1}w_j)+\alpha+4)\frac{w_i}{v}-\frac{8R}{v},$$
$$i=2,...,K \quad (12)$$

From Eq. 11 and Eq. 12, traveling time of MDC T_i can be obtained as a function of the width of the level and the arc angle of a cone. Therefore, MIN-PD problem is rewritten as

$$\text{minimize} \quad \tau \quad (13)$$

$$\text{subject to} \quad \frac{\alpha w_1^2}{2vR}+(\alpha+4)\frac{w_1}{v}\le\tau \quad (14)$$

$$\frac{\alpha w_i^2}{2vR}+(\frac{\alpha}{R}(\sum_{j=1}^{i-1}w_j)+\alpha+4)\frac{w_i}{v}-\frac{8R}{v}\le\tau,$$
$$i=2,...,K \quad (15)$$

$$\sum_{i=1}^{K}w_i=d \quad (16)$$

3. Finding the Solution for MIN-MDC problem

In this section, we present optimization formulation to find the solution for the second problem. Recall that α represents the arc angle of a cone, and $\alpha=\frac{2\pi K}{N}$,where K and N represent the number of levels and the number of MDCs, respectively. By substituting $\alpha=\frac{2\pi K}{N}$ into Eqs. 11 and 12, the traveling time of MDCs, $F_i(i=1,...,K)$, can be calculated as

$$F_1(w,N)=\frac{\pi K}{2vRN}w_1^2+(\frac{\pi K}{N}+2)\frac{w_1}{v} \quad (17)$$

$$F_i(w,N)=\frac{\pi K}{2vRN}w_i^2+(\frac{\pi K}{RN}(\sum_{j=1}^{i-1}w_j)+\frac{\pi K}{N}+2)\frac{w_i}{v}-\frac{4R}{v},$$
$$i=2,...,K \quad (18)$$

From Eq. 17 and Eq. 18, the traveling time of MDC F_i can be obtained as a function of the width of the level and the number of MDCs. Therefore, the second problem is equivalent to

$$\text{minimize} \quad N \quad (19)$$

$$\text{subject to} \quad \frac{\pi K}{2vRN}w_1^2+(\frac{\pi K}{N}+2)\frac{w_1}{v}\le t \quad (20)$$

$$\frac{\pi K}{2vRN}w_i^2+(\frac{\pi K}{RN}(\sum_{j=1}^{i-1}w_j)+\frac{\pi K}{N}+2)\frac{w_i}{v}-\frac{4R}{v}\le t,$$
$$i=2,...,K \quad (21)$$

$$\sum_{i=1}^{K}w_i=d \quad (22)$$

By using the interior-point algorithm for a given set of parameters, the solutions are obtained for both problems.

IV. Numerical Study

In this section, a detailed numerical study of the proposed scheme is demonstrated. In order to validate the proposed method, a circular area with a radius (d) of 500 m is considered. The sink is placed at the center of the area. The MDCs move at a speed (v) of 10 m/s, and the sensing range (R) is 20 m. These parameters and MATLAB are used to solve both optimization problems.

1. Numerical Results for MIN-PD problem

This subsection presents numerical results for MIN-PD problem that show the minimum traveling time for the given MDCs. The number of MDCs, N, considered for this analysis is from 1 to 6. The minimum traveling time of MDCs, τ , is acquired at different levels using the different numbers of MDCs. These results are depicted in Fig. 2. To obtain the optimal solutions, random initial values are tested. Depending on the number of MDCs, the entire area is divided into different levels. To achieve the minimum traveling time of MDCs, every level should have at least one MDC. We cannot obtain the minimum traveling time of MDCs when every level does not have at least one MDC.

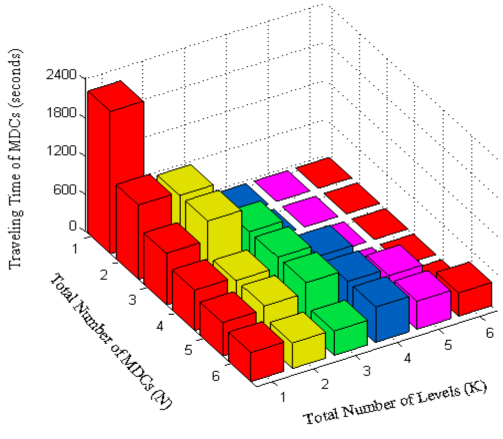

그림 2. 레벨수와 MDC 개수에 따른 MDC의 최소 이동 시간에 대한 영향
Fig. 2. Effects of levels and MDCs on minimum traveling time of MDCs

Fig. 2 shows that the minimum traveling time of MDCs tends to decrease for every level when the number of MDCs increases. Moreover, as shown in Fig. 2, when the number of levels in the entire area is high, the shortest traveling time for the given MDCs is achieved. From Fig. 2, we also observe that the traveling time of MDCs tends to decrease with slight fluctuations as the number of levels grows for different numbers of MDCs. The reason is that an equal number of MDCs is considered for every level in our scheme.

More specifically, we cannot use all given MDCs in some cases. For example, if the total number of MDCs (N) is 5, then we divide the entire area up to five levels. We can use all 5 MDCs when the total number of levels (K) in the entire area is 1 and 5. For K= 2,3, and 4, respectively, the number of MDCs (N) used is 4, 3, and 4. As a result, in some cases, when the number of levels increases, the traveling time of MDCs increases as well.

2. Numerical Results for MIN-MDC problem

This subsection presents numerical results for the second problem that show the minimum number of MDCs needed to satisfy the given delay bound of packets. For the analysis, different delay bounds, t, are considered, such as 200, 300, 500, 900, and 1500 seconds. The second problem is also solved using the interior-point algorithm with random initial values.

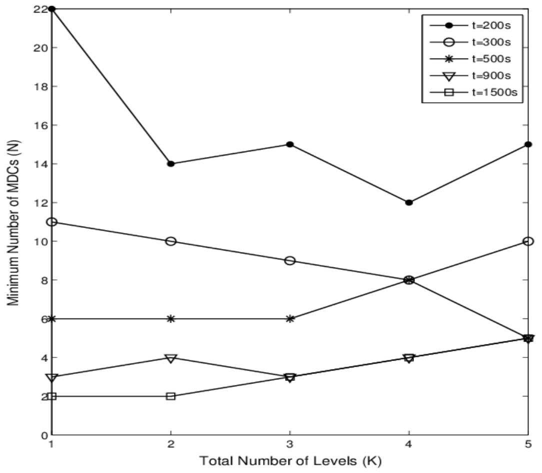

그림 3. 최소 필요 MDC수에 대한 레벨수의 영향
Fig. 3. Effects of levels on the minimum number of MDCs

Fig. 3 shows the minimum number of MDCs at different delay bounds of packets when the number of levels in the entire area varies from 1 to 5. As shown in Fig. 3, when the delay bound increases, the minimum number of MDCs decreases for every level.

Fig. 3 also illustrates that the minimum number of MDCs (N) tends to decrease with slight fluctuations as the total number of levels (K) increases for different delay bounds. The reason is that every level needs to have an equal number of MDCs in our scheme. As a result, when K grows from 1 to 5, the minimum number of MDCs decreases with some fluctuations with every delay bound of packets.

V. Conclusion

In MDC-based data gathering schemes, MDCs are used to collect data from the environment. In order to achieve minimum packet delay using the given MDCs, and to obtain the minimum number of MDCs for a given delay bound of packets, two optimization problems are defined and formulated in this paper. To solve these problems, the traveling distance and the traveling time of MDCs are estimated. The interior-point algorithm with random initial values has been used to obtain the optimal solutions. Numerical results demonstrate that the proposed method can achieve the minimum traveling time and minimum number of MDCs.

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