Performance Evaluation of Intercluster Multi-hop Communication on Large-scale Sensor Networks

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Abstract

In large-scale sensor networks, multi-hop communication between sensor nodes is necessary to cover a large monitoring region. Moreover, sensor nodes should be grouped into clusters to enhance scalability and robustness. We examine the characteristics of multi-hop communication between clusters in large-scale sensor networks and compare them with other routing methods.

We also investigate the characteristics of sensor networks by comparing TDMA with CSMA/CA. If positional information of all sensor nodes is available, a transmission schedule that avoids interference completely can be constructed and TDMA can be applied. However, gathering this information and distributing the schedules over large monitoring region are impossible practically. Therefore, we also apply CSMA/CA since the information of only neighboring sensor nodes is necessary. As a result, using CSMA/CA, power consumption increases by 12% *and the packet collection time becomes about four times longer in comparison to using TDMA based on location information of all sensor nodes.*

Keywords: sensor network, clustering, multi-hop communication, simulation, interference

1. Introduction

Various applications of sensor networks have been investigated, such as disaster prediction, security, environmental monitoring, and traffic control. A wide variety of network sizes are used in these applications. In environmental monitoring, for example, hundreds or thousands of sensor nodes are deployed in a large monitoring region. In such large-scale sensor networks, scalability and robustness are very important. In addition, sensor nodes are highly power-constrained, and sensor nodes must work at very low power consumption as much as possible to prolong the lifetime of the sensor network. Clustering, a method of grouping sensor nodes, can meet these requirements and it has been the focus of much research on sensor networks. Therefore, clustering schemes have been extensively studied [1-7]. In addition, the communication ranges of sensor nodes are generally short. So, to collect data from a large monitoring region, multi-hop communication is necessary.

As noted above, a combination of clustering and multi-hop communication is useful for collecting data on large-scale sensor networks. Therefore, some studies on sensor networks using multi-hop communication between clusters have already been performed [8-11]. However, existing research does not sufficiently provide the distribution of power consumption over a monitoring region. When considering the operating time of sensor networks, knowing where power depletion occurs and how it affects the connectivity between sensor nodes is important. Also, imagine that many sensor nodes are densely placed in a monitoring region. In this case, many sensor nodes are in the communication range of each other. Therefore, the transmission of a sensor node could likely interfere with transmissions of other sensor nodes. If positional information of all sensor nodes can be used, constructing a schedule of their transmissions that avoids interference between transmissions with TDMA (Time Division Multiple Access) is possible. However, such a strategy is not realistic in view of the overhead to gather all positional information and distribute transmission schedules over a monitoring region. That means multiple access methods using positional information of only local sensor nodes in the large-scale sensor networks must be used. So, the characteristics of the multiple access methods must be clarified in this case.

We aim at showing the distribution of power consumption over a monitoring region and the impact on power consumption when using multiple access based only on local positional information in large-scale sensor networks with multi-hop communication between clusters. We construct a transmission schedule that avoids interference completely based on positional information of all sensor nodes. Additionally, we determine the fundamental traits of sensor networks with multi-hop communications between clusters using the schedule. Furthermore, we evaluate the power consumption and data collecting time when CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) is applied as a multiple access method to avoid data losses caused by interference. With this evaluation, we determine how much performance degradation occurs by retransmission induced by interference.

In Section 2, we present related studies on both clustering and multi-hop communication between clusters. In Section 3, we explain our network model. In Section 4, we clarify the fundamental characteristics of sensor networks with multi-hop communication between clusters by comparing them with other routing methods through the analysis and simulation experiments. In Section 5, we discuss the degree of performance degradation when applying CSMA/CA compared with when using an ideal transmission schedule with a TDMA mechanism. Finally, in Section 6, we conclude.

2. Related work

In sensor networks, a low-energy adaptive clustering hierarchy (LEACH) has been proposed as a clustering method for reducing power consumption of sensor networks [5]. In LEACH, each sensor node decides whether to become a cluster-head based on a predetermined percentage. Clusters are constructed by sensor nodes adjacent to cluster-heads. Communication from sensor nodes to cluster-heads and communication from cluster-heads to a sink node is performed via a single hop.

Many clustering methods to improve LEACH have been suggested. In LEACH, the positions of clusters can be unbalanced, decreasing the network lifetime. Hybrid energy-efficient distributed clustering (HEED) [7] places clusters uniformly over a monitoring region. Furthermore, HEED balances power consumption between sensor nodes. The central controlling algorithm, which provides a regular cluster size, was also proposed [4]. The time complexity of this algorithm is $O(n^3)$, where n is the number of sensor nodes. Although LEACH uses single-hop communication within a cluster, hybrid indirect transmissions (HIT) [3] uses multi-hop communication within clusters to limit the interference range and to communicate in parallel with as many nodes as possible.

Reduction of the transmission distance is needed to minimize the power consumption of sensor networks. From this standpoint, power-efficient gathering in sensor information systems (PEGASIS) [6] comprises a chain instead of clusters. This chain connects the nearest neighboring sensor nodes, and the distance between sensor nodes is very short. Two-Phase Clustering (TPC) [2] also constructs chains within clusters.

Research has also been done on multi-hop communication between clusters in sensor networks. In connectionless probabilistic (CoP) routing [9], the monitoring region is divided into square areas. Then, multi-hop communication between cluster-heads positioned at vertices of these areas was performed. Assuming that the sink node is able to communicate with all sensor nodes directly, Neander *et al.* evaluated a sensor network using multi-hop communication between cluster-heads mainly through simulation experiments [8]. The unequal clustering size (UCS) [11] was designed to equalize the power consumption among cluster-heads. In UCS, a circular monitoring region is split into two concentric circles, called layers. Soro and Heinzelman determined the size of the cluster in the interior layer should be reduced to equalize the power consumption. Shu *et al.* divided a monitoring region into multiple layers and derived optimal parameters, such as the cluster radius of each layer and the relay probabilities of cluster-heads, to prolong the coverage-time. However, these studies did not completely represent the performance of general multi-hop communication. They evaluated only power consumption or used a limited number of clusters in their simulation experiments.

3. Sensor network model

3.1. Network model

A model of the sensor network under consideration is as follows. The sink node is placed at the center of the region. Reduction of data volume by data fusion is not performed. That is, data generated by sensor nodes is transmitted to the sink node without any modification or compression. Sensor nodes are placed randomly and uniformly. We assume that both the sink node and the sensor nodes are stationary after deployment. All sensor nodes have the same initial power and communication capabilities. Moreover, they have the ability to control the transmission power depending on the distance between the sensor node and its next-hop node. We also assume that sensor nodes are synchronized with each other and they send and receive data in synchronization with fixed-length timeslots. The same wireless channel is used in the entire network for the intra-cluster communication and another one is used between cluster-heads.

When a sensor node receives multiple packets at the same time, the node cannot receive both packets correctly. We denote this situation as interference of data. To take this interference into account, we use the model presented in [3]. To illustrate the interference of data, consider four sensor nodes shown in Fig. 1. Sensor node n_i sends a packet to sensor node u_i located a distance r_i from n_i, and n_j sends a packet to u_j located at distance r_j from n_j. In this case, sensor node u_i receives packets from n_i and from n_j simultaneously and thus cannot receive packets. This condition is represented in (1). That is, the interference of data occurs when n_i and n_j, which satisfy (1) send data simultaneously. $d(u_i, n_j)$ in (1) corresponds to the distance between sensor node u_i and n_j.

$$d(u_i, n_j) < r_j \tag{1}$$

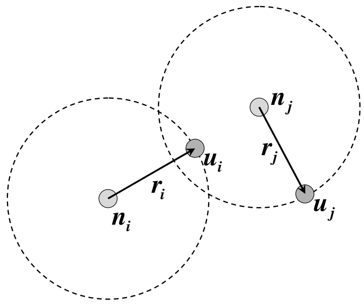


Figure 1. Data interference.

3.2. Power consumption model

The lifetime of sensor networks depends on the operation time of individual sensor nodes. Therefore, a model, which defines the amount of power consumed in each action of a sensor node, influences the lifetime of networks to a great degree. We used the power consumption model represented in [5]. That is, the power needed to transmit k bits of data over a distance d is

$$E_{T_x} = E_{elec}k + \epsilon_{amp}kd^2 \tag{2}$$

and the power needed to receive k bits of data is:

$$E_{R_x} = E_{elec}k \tag{3}$$

3.3. Routing

Using multi-hop communication between clusters, a sensor node must determine its next-hop node. For simplicity, only the distance to the next hop is used as a selection criterion in choosing a relay node. For example, the procedure for selecting a relay node within a cluster is as follows. In Fig. 2, n_s represents a sensor node that transmits a packet, r_{max} is the maximum communication range, n_i is the next-hop node of n_s, and CH_{n_s} represents the cluster-head of n_s. n_s selects the nearest sensor node that satisfies the following three equations as its next-hop node.

$$d(n_i, CH_{n_s}) < d(n_s, CH_{n_s}) \tag{4}$$
$$d(n_s, n_i) < d(n_s, CH_{n_s}) \tag{5}$$
$$d(n_s, n_i) \leq r_{max} \tag{6}$$

Equation (4) indicates that the next-hop node is closer to the cluster-head than the sending node. Equation (5) represents that the power of the sending node needed to transmit a packet to its next-hop node is smaller than the power needed to transmit a packet to its cluster-head. Equation (6) indicates the next-hop node is located within the maximum communication range of the sending node. If n_i does not exist and $d(n_s, CH_{n_s}) \leq r_{max}$ is satisfied, the next-hop node of n_s is cluster-head CH_{n_s}. The same is true for the procedure for selecting the next-hop cluster-head in multi-hop communication between cluster-heads.

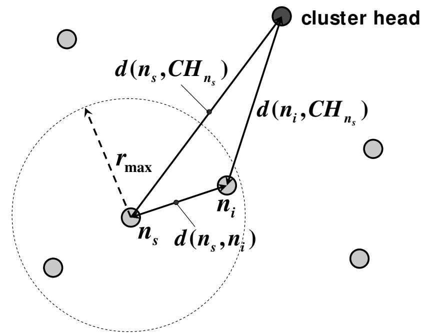


Figure 2. Procedure for selecting relay node within a cluster.

4. Fundamental characteristics of multi-hop communication between clusters

4.1. Construction of transmission schedule without interference

In our interference model, the condition of interference is described only based on the distance between sensor nodes. If positional information of all sensor nodes is available, a transmission schedule can be constructed that eliminates data interference. Therefore, communications with a TDMA mechanism are possible. To create the schedule, we use the algorithm of autonomously constructing a transmission schedule proposed in Culpepper *et al* [3]. In our simulation experiments, each sensor node follows this schedule, and they transmit packets to their next-hop sensor nodes at assigned timeslots. This transmission is free from interference. In addition, because we assumed that no transmission errors occur, packets are received by the next-hop sensor nodes without errors. All packets arrive at the sink node at predetermined times.

4.2. Simulation setting

To clarify the fundamental characteristics of multi-hop communication between clusters, we use the following three routing methods as objects for comparison with LEACH+multi-hop and HEED+multi-hop.

- Each sensor node communicates with the sink node directly (direct).
- After clusters are constructed, each sensor node transmits a packet to its cluster-head, and the cluster-heads send those packets and their own packet to the sink node directly (LEACH).
- Each sensor node sends packet to the sink node in a multi-hop fashion without clustering (multi-hop).

Table 1. Parameter setting.

parameter	value
Radius of a monitoring region	500 m
Number of sensor nodes	500
Initial Power	2 J
Maximum communication range	300 m
E_{elec}	50 nJ/bit
ϵ_{amp}	100 pJ/bit/m^2
Length of data packet	2000 bits

Using multi-hop communication, each sensor node needs to determine its next-hop intermediate node as previously mentioned. Therefore, not only in HEED+multi-hop and LEACH+multi-hop but also in multi-hop, we apply the routing method described above (in 3.3) to them.

The parameter values used in our simulation are listed in Table 1. We assume that sensor nodes perform sensing and generate packets simultaneously. After the sink node receives all packets that can reach it, sensor nodes perform sensing again. We define this period as a cycle. In routing methods that construct clusters, rotating the role of a cluster-head between sensor nodes is necessary once in a period, called a round, to prevent cluster-heads from depleting large amounts of power. Though control signals, such as cluster-head advertisements, are sent and received for every round and the power of sensor nodes is consumed, we define the length of a round to be the same as the length of a cycle. That is, clustering is performed every cycle. Our simulation results are the average values obtained over 100 simulations.

When using multi-hop communication between clusters, determining the percentage of cluster-heads is necessary. We define the data collection rate as the portion of packets arriving at the sink node in all transmitted packets and investigate the change in the data collection rate using LEACH and HEED as clustering methods. As a result, the percentage of cluster-heads has little influence on the change of the data collection rate. We use 20% as the percentage of cluster-heads because at this values a high data collection rate can be maintained for a slightly longer time.

4.3. Evaluation of power consumption by analysis and simulation

We have proposed a method for analytically deriving power consumption of multi-hop communication between clusters [12]. For formulation, we introduced two assumptions in the analytical model. First, distances of transmission of both sensor nodes and cluster-heads are constant (i.e., transmission power control is not performed). Second, in the routing between cluster heads, the relay is done to the adjacent cluster in the direction of the sink node. Here, we summarize our analytical method.

Our approach extends the method of [13] to the system which performs the multi-hop communication between clusters. Assuming clusters are circular form, we derive the total number of transmissions in a cluster, x_c, is

$$x_c = \sum_{h=1}^{\lceil \frac{l}{r} \rceil} N_c\{1 - (h-1)^2 \frac{r^2}{l^2}\} \tag{7}$$

where l is the radius of a circular cluster, r is the transmission range of a sensor node, h is the hop count of each sensor node from the cluster-head, and N_c is the number of sensor node in each cluster respectively. Then we can obtain the total energy E_c required to collect data to the cluster-head of a certain cluster as follows:

$$E_c = x_c(E_{elec}k + \epsilon_{amp}kr^2) + x_c E_{elec}k \tag{8}$$

where k is the length of a data packet.

Next, we derived energy consumption when the node acts as a cluster-head. To do this, we take notice of cluster-heads in a circular domain of width r_{CH} and whose distance from a sink node is between $d - r_{CH}$ and $d + r_{CH}$ as shown in Fig. 3, where r_{CH} is the transmission range of the cluster-head. These cluster-heads in the circular domain will receive the data generated by all the sensor nodes located outside that domain and will relay it to the sink node or a cluster-head closer to the sink node. For simplicity, the data relayed from outside that domain shall be equally divided among the cluster-heads in the domain. Furthermore, cluster-heads transmits data from sensor nodes in their own cluster. From these thought, we can obtain the energy consumption in the case of the usual sensor node and in the case of a cluster-head. The results of both analysis and simulation experiments are shown in Fig. 4. These results are obtained with 2000 sensor nodes, a radius of 300 m monitoring region, and 20 m of communication range of a sensor node. Though the parameters are different from parameters represented in Table. 1, the result of analysis and that of simulation experiments is in good agreement when transmission power control is not performed and communication range is fixed.

Since transmission power control is disabled in our analytical model, we obtain the average transmission distances between sensor nodes and between cluster-heads by simulation experiments, and apply our analytical approach with these values. This result is plotted in Fig. 5. In the method of simply repeating data relay, as mentioned in [12], power consumption grows larger as approaching the sink node. This is because power consumption for relaying data near the sink node is accumulated and transmission power control is not performed. In the analytical model, excessive power could be used in transmission. On the other hand, just minimum power enough to communicate with a next-hop node is consumed in our simulation experiments. Compared with the curve of analysis, other methods can reduce concentration of power consumption near the sink node.

In the simulation experiments, if a region exists where sensor nodes are located that cannot transmit packets to the sink node directly, comparing routing protocols is difficult because not all packets can reach the sink node. Therefore,

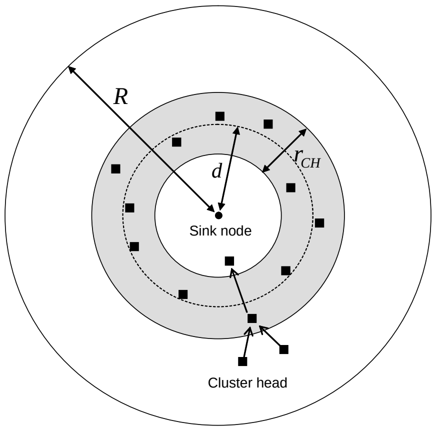


Figure 3. The data generated outside of a circular area is relayed via the cluster-heads in that area, and sent to the inner area.

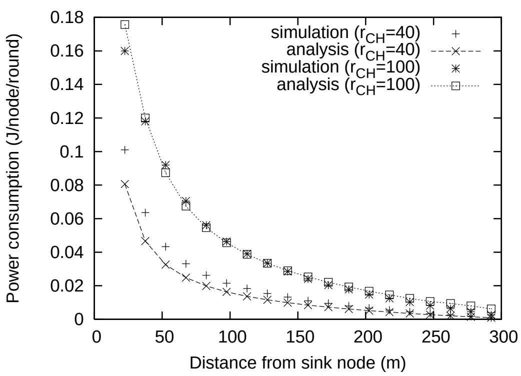


Figure 4. Relationship between distance from sink node and power consumption of sensor nodes derived by analysis and simulation.

for direct and LEACH, we set the maximum communication range to 500 m.

From Fig. 5, multi-hop communication between sensor nodes without clustering generates a region in which the sensor node consumes the largest amount of power (25 – 50 m from the sink node) except the analysis. This is because the sensor nodes in the region must relay enormous numbers of packets of other sensor nodes farther away from themselves. However, multi-hop communication between cluster-heads can reduce power consumption since the role of cluster-heads is rotated between sensor nodes, and the load of relaying is dispersed among them, as compared with multi-hop communication without clustering. Also, the region where the largest amount of power is consumed is the area 100 m from the sink node. The main reason for this is the probability that other cluster-heads located inside this area is low, and cluster-heads in this area must communicate with the sink node directly without relays.

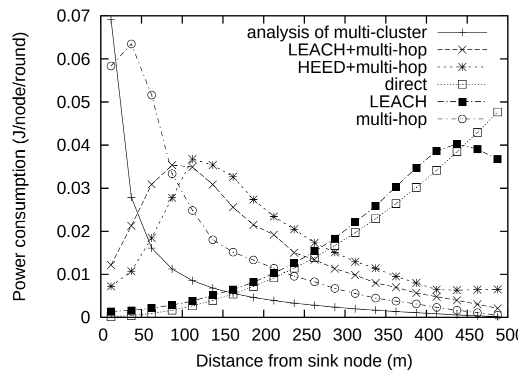


Figure 5. Comparison of power consumption for various routing protocols.

In LEACH and direct, which use direct communication from sensor nodes to the sink node, the longer the distance from the sink node is, the larger the power consumption is. Comparing with LEACH and direct, the former has a larger power consumption than the latter. It is because of the power consumed by exchanging control signals accompanied by clustering.

4.4. Deterioration of data collection rate due to power depletion of battery

Maintaining a high data collection rate as long as possible is important, because the data collection rate determines the lifetime of sensor networks. The data collection rate per round is shown in Fig. 6. In this figure, each curve, which represents the data collection rate of a different routing method, behaves similarly until about 80 rounds. However, the positions of exhausted sensor nodes in each method make a difference, as shown in Fig. 5. To make this difference clearly understandable, we visualized these distribution of exhausted sensor nodes of LEACH and HEED+multi-hop in Figs. 7(a) and 7(b), respectively. These figures represent the situation of sensor networks at 80 rounds. The filled circle at the center of the monitoring region is the sink node. Small filled circles and open circles represent sensor nodes that have residual power or exhausted sensor nodes, respectively. Solid lines are the communication links within a cluster, and dotted lines are the communication links from a cluster-head to the sink node and between cluster-heads. In LEACH and direct, as shown in Fig. 7(a), sensor nodes on the fringe of the monitoring region exhaust their power first since these nodes must transmit packets to the distant sink node in a single-hop. Due to their power depletion, the packet collection rate starts to decrease early. As time goes by, however, the packet collection rate curves for LEACH and direct drop slower than the other methods. This indicates a situation where only sensor nodes near the sink node have residual power, as in Fig. 7(a). These sensor nodes can operate for many rounds

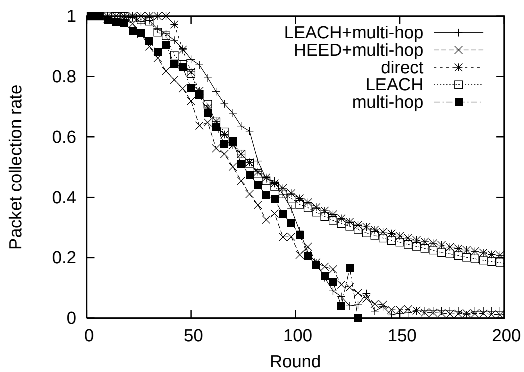
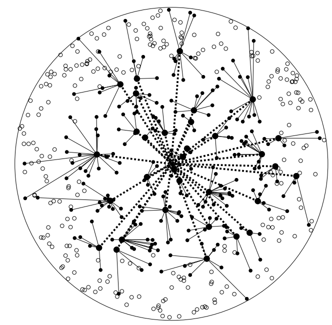
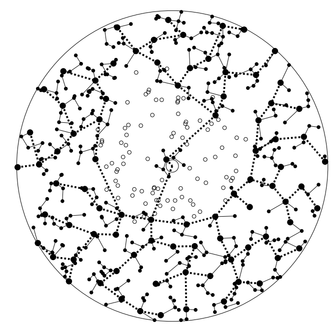


Figure 6. Deterioration of data collection rate due to power depletion.

since the transmission power needed to reach the sink node is comparatively small. However, non-uniform distribution of the residual power is undesirable in sensor networks because of the need to collect data over the entire monitoring region. As shown in Fig. 7(b), unbalanced distribution of the residual power also occurs in HEED+multi-hop. In this routing method, the sensor nodes near the sink node deplete their power early also. The same can be said for the other two routing methods using multi-hop communications (i.e., LEACH+multi-hop and multi-hop). With power depletion near the sink node, gathering information about the region becomes impossible as time goes by. In addition, obtaining information about the fringe of the monitoring region also becomes difficult. Because of these factors, the data collection rate continues to fall sharply.



(a) LEACH



(b) HEED+multi-hop

Figure 7. Situations at 80 rounds in (a) LEACH and (b) HEED+multi-hop.

4.5. Data collection time

The data collection time is an important metric in real-time applications. A graph of the data collection time is shown in Fig. 8. Because we set the number of sensor nodes to 500, the number of packets the sink node receives is 500. Therefore, the minimum time to collect all the data is 500 timeslots. LEACH and direct have this minimum time and are optima for the data collection time. In direct, 1 timeslot is simply assigned to each sensor node to avoid transmitting data simultaneously with other sensor nodes. Also, for LEACH, while a cluster-head communicates with the sink node, other cluster-heads can collect data from sensor nodes in their clusters. Then, a transmission schedule that is free of interference and has an optimal data collection time can be constructed.

In sensor networks using multi-hop communication, the amount of data arriving at the sink node does not grow linearly with time, regardless of whether clusters exist. The reason for this is that packets generated by sensor nodes far away from the sink node take a long time to reach the sink node. With clusters constructed, the data collection time decreases slightly compared to the case without clusters. This is because the hop counts to the sink node are kept low by transmissions only between cluster-heads.

5. Applying CSMA/CA to sensor networks

In the previous section, we evaluated the fundamental characteristics of multi-hop communication between clusters on the assumption that ideal transmission scheduling can be constituted using positional information of all sensor nodes. In large-scale sensor networks, however, use of information about all sensor nodes is not a realistic approach, and construction of a schedule that completely avoids interference is difficult. Therefore, when no positional information can be used, we apply a CSMA/CA mechanism instead of a TDMA mechanism based on the schedule, and we organized the network in a distributed manner.

The CSMA/CA mechanism we use is based on IEEE 802.15.4 [14]. Each sensor node maintains a variable backoff exponent (*BE*). The *BE*s are used for determining the length of random waiting times before evaluating the status of a channel. The transmission algorithm is shown in Fig. 9. Generally, in CSMA/CA, the maximum number of backoffs is provided, and if the number of the backoff reaches this

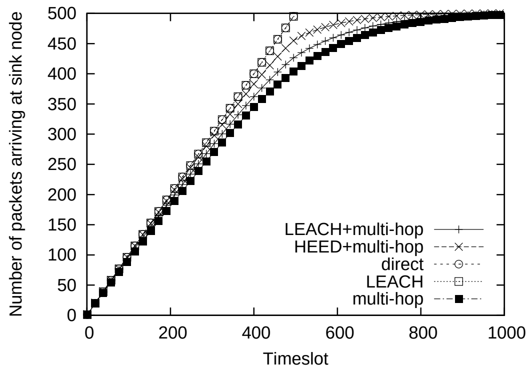


Figure 8. Data collection time for different routing protocols.

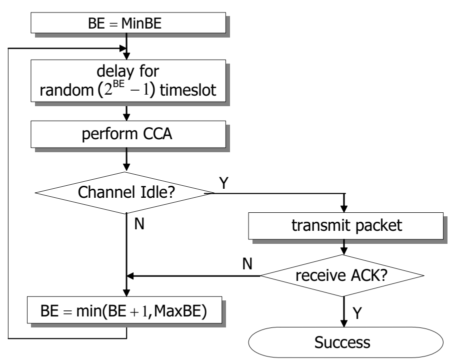


Figure 9. Transmission algorithm of CSMA/CA.

threshold, the sensor node aborts its transmission attempt. Here, however, the sensor node backs off as many times as needed to pay attention to the influence of retransmission caused by the interference of data. The values of both *MinBE* and *MaxBE* are set to 3 and 5 respectively. These values are the defaults of IEEE 802.15.4.

Retransmissions are needed even when using a CSMA/CA mechanism because of the hidden terminal problems. Besides, backing off must be done before carrier sensing in the CSMA/CA. Due to these factors, both the power consumption and the data collection time should increase. HEED+multi-hop with CSMA/CA and HEED+multi-hop with TDMA based on an ideal transmission schedule are investigated.

5.1. Comparison of power consumption

A comparison of the power consumption levels of a sensor node is shown in Fig. 10. Over a monitoring region, the power consumption of sensor networks with CSMA/CA is larger than that of sensor networks with TDMA using an ideal transmission schedule. This is because of retransmission caused by interference. Even if we use CSMA/CA,

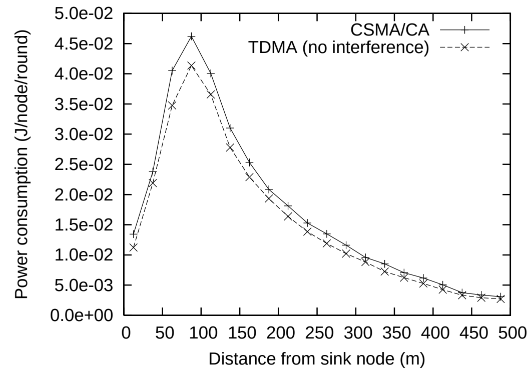


Figure 10. Comparison of power consumption per node with CSMA/CA and TDMA avoiding interference.

data interference cannot be avoided completely, as noted above. In this case, the sensor node transmits data at least twice. The first time is the transmission that causes interference, and the second is retransmission. The closer the sensor nodes are located to the sink node, the more data is relayed. Then, the probability of interference for transmissions of these sensor nodes increases. The sensor node one-hop from the sink node (the last-hop node) relays the largest number of packets, and the smaller the percentage of the cluster-heads is, the longer the distance between last-hop nodes and the sink node is. Therefore, the transmission power of the last-hop node is increased. These factors make the power consumption of the region $75-100$ m from the sink node maximal when the percentage of the cluster-heads is 20%. This region corresponds with the region where the largest power is needed when using TDMA based on the positional information of all sensor nodes. The main problem is collecting data from this region becomes impossible due to the power depletion of the sensor nodes in the region. Therefore, obtaining a distribution of power consumption is important.

We define E_{TDMA} as the power consumption with TDMA using a transmission schedule that avoids interference, and $E_{CSMA/CA}$ as the power consumption with CSMA/CA. We also define the percentage increases as $\frac{E_{CSMA/CA}-E_{TDMA}}{E_{TDMA}}$. By calculating the average of the percentage increases over the monitoring region, the power consumption with CSMA/CA increases by 12% compared with the power consumption with TDMA.

5.2. Comparison of data collection time

A backoff period is necessary before evaluating the status of a channel in CSMA/CA, and the data collection rate may decrease compared with TDMA. A comparison of the data collection rates is shown in Fig. 11. Compared with TDMA using a transmission schedule, the period to collect 90% of packets is 3.7 times longer. In large-scale sensor

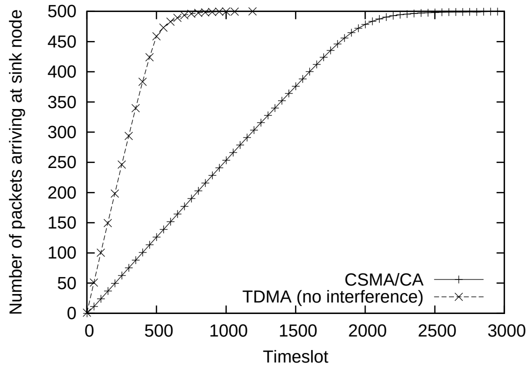


Figure 11. Comparison of data collection rates.

networks where many sensor nodes are densely deployed, when a sensor node tries to transmit a packet, channels are often busy due to the transmission of other sensor nodes. Therefore, backing off is needed many times. A sensor node close to the sink node must transmit packets more frequently than others, and the number of backing off is also large. As a result, the data collection time increases. From these characteristics, careful consideration is needed when a sensor network with large hop counts is applied to an application requiring real-time performance.

6. Conclusion

We investigated the fundamental characteristics of large-scale sensor networks using multi-hop communication between and within clusters. As a result, the relaying load of the sensor nodes closer to the sink node was decreased as compared with sensor networks without clustering. We also compared sensor networks using CSMA/CA with those using TDMA that avoids interference completely. To collect the same amount of packets, the power consumption increased by 12%, and the data collecting time was 3.7 times longer when using CSMA/CA. We showed that retransmissions accompanied by interference affected the power consumption, and that the backoff time of CSMA/CA impacts the data collection rates of nodes. Except for interference, transmission errors can cause retransmissions. Therefore, we will evaluate the influence of the errors over the wireless transmission channel on sensor network performance in the future.

Acknowledgement

This research was partly supported by “New Information Technologies for Building a Networked Symbiosis Environment” (The 21st Century Center of Excellence Program), Grant-in-Aid for Scientific Research (C) 17500043, and Grant-in-Aid for Scientific Research (A)(2) 16200003 of the Ministry of Education, Culture, Sports, Science and Technology, Japan. The authors would also like to thank Dr. Kenji Leibnitz for his detailed comments.

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