An Energy-Efficient Routing and Reporting Scheme to Exploit Data Similarities in Wireless Sensor Networks[*]

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Abstract. Wireless sensor networks are based on a large number of tiny sensor nodes, which collect various types of physical data. These sensors are typically energy-limited and low-power operation is an important design constraint. In this paper, we propose a novel routing and reporting scheme based on sample data similarities commonly observed in sensed data. Based on reliable transport protocols, the proposed scheme takes advantage of the spatial and temporal similarities of the sensed data, reducing both the number of sensor nodes that are asked to report data and the frequency of those reports. Experimental results show that the proposed scheme can significantly reduce the communication energy consumption of a wireless sensor network while incurring only a small degradation in sensing accuracy.

1 Introduction

A wireless sensor network is made up of a large number of tiny sensor nodes which are organized to collect various types of physical data such as temperature and sound in a cost-effective manner [1]. These tiny sensors (e.g., Mote [2] and Smart-Its [3]) are interconnected by unreliable radio channels which are used to construct ad-hoc routing paths. The routing paths are mainly used to deliver collected data from sensor nodes to base nodes where the sample data are analyzed for further services. Due to their relative ease of construction, practitioners have recently been trying to use these wireless sensor networks for monitoring and collecting data.

In general, the sensor nodes are severely limited in their energy resources, so a paramount concern in designing wireless sensor networks is the efficient use of a given energy budget. In particular, as reported by Hill, Culler, and their colleagues [4, 5], a large portion (up to 60%) of the total energy consumption is by radio devices used for communications. Thus, the support of energy-efficient communication surfaces as the main challenge in extending the lifetime of a wireless sensor network.

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In practice, a large amount of communication energy is wasted because the radio devices used in sensor networks have a packet error rate of up to 50% [6]. In order to avoid wasted packets becoming lost during the transmissions, reliable communication protocols such as RMST [7] and ARQ [8] can be used. These protocols ensure the complete end-to-end message delivery, but they make it more expensive to send a single packet. However, sensor networks are often used for the reliable detections of events that affect the network as a whole, and not just an individual sensor node. Partially reliable schemes for data transport have been recently developed to reduce the overall energy consumption of reliable communication protocols [9, 10]. Partially reliable transport can ensure that a certain fraction of sensor nodes reliably reports their data to the base nodes.

In order to improve the energy efficiency of these partially reliable schemes, we propose a novel routing and reporting scheme that exploits data similarities in wireless sensor networks. Our main motivation comes from two observations. First, most of the data collected from sensor nodes exhibit high *spatial similarity*, a term which refers to the tendency for adjacent sensor nodes to be sensing comparable data at a given point in time. To exploit this spatial similarity, only the data from chosen header nodes is routed while the remaining nodes in a group of adjacent nodes are managed in a power saving mode. The radius of these groups can be specified by users depending on the type of data to be sensed. The header nodes are chosen partly by consideration of their remaining battery capacity, so our proposed routing method simultaneously guarantees the uniform use of all the sensors' batteries.

Second, we observe that various types of sensed data have a strong *temporal similarity* which predicts that a sensor - even a header - is very likely to be sensing similar data to that recently sensed. Therefore, in our proposed reporting method, sensor nodes report data only when it is sufficiently different from the most recent report. We call this minimum difference the degree of quantization, and it can be specified by users depending on the data type.

For the delivery of reporting data, we use a reliable MAC channel, which is specifically optimized to reduce both communication time and energy. Although only part of sensed data is delivered to base nodes, missing data can be *interpolated* [11]. If users set the routing radius and quantization degree correctly, our proposed scheme can significantly reduce the communication energy consumption without sacrificing sensing accuracy.

To evaluate its performance, we developed a byte-level sensor network simulator and used real-world measured data for experiments [12]. The experimental results show that our proposed routing method can turn off 28-66% of all sensor nodes, and the proposed reporting method can reduce the radio energy consumption of each header node by 72-96%, with degradation in the sensing accuracy less than 5%.

The rest of this paper is organized as follows. In Section 2, we describe our proposed routing and reporting scheme. The experimental methodology is explained in Section 3 while the evaluation results are given in Section 4. We review related works in Section 5. In Section 6, we conclude this paper.

2 Data Similarity Aware Sensor Network Management

We assume that the main user interface to a wireless sensor network will be a SQL-style query [13, 14]. We have extended the SQL-style query syntax to support temporal and spatial similarities of sensed data explicitly. We assume that users send data collection requests to the sensor network using the following syntax:

```
SELECT {sample_type}+ FROM sensors
WHERE {condition}
SAMPLING PERIOD {time_interval_1}
DURATION {time_interval_2}
[ROUTING RADIUS {numeric_1}]
[QUANTIZATION DEGREE {numeric_2}]
```

This query requests collection of the specified *sample_types* from sensor nodes that satisfy *condition* in every *time_interval_1* during the duration of *time_inter−val_2*. Optionally, users can specify the routing radius *numeric_1* and the quantization degree *numeric_2* to indicate the desired spatial similarity and temporal similarity. When a user requests a query, it is translated into a routing packet in the base node, and that packet is disseminated to all sensor nodes as described in Section 2.1.

2.1 Spatial similarity based routing method

We will consider a school building where several sensor nodes are installed, as shown in Figure 1. If the base node 1 tries to gather temperature or voice samples from the whole building, a large proportion of the sensor nodes do not have to report their sample data because the values sensed in a single room will typically be quite similar to each other. In this example we can elect one sensor node per every room as a router node to reduce the energy consumption without sacrificing sensing accuracy. Here, we use the room size as the routing radius.

In critical sensor networks such as those monitoring enemy behavior, sensors are randomly scattered and several may end up being located very close together. In this case, although the sensed data does not exhibit the spatial similarity, we are also able to exclude adjacent sensor nodes from the routing path to eliminate duplicated reports.

A spatial similarity aware routing path is built in the following manner, as shown in Figure 1. A base node 1 broadcasts a routing packet to its neighbor nodes. As the base node controls the radio signal strength, the packet can be delivered to sensor nodes located within the specified routing radius. In this example, as the radius is the maximum internal length of a room, sensor nodes 2, 3, and 4 are able to receive the packet, while nodes 5 and 6 cannot receive it due to interference by the walls.

When a node firstly receives a routing packet, it simply admits the packet and notes the routing depth value that is contained in the packet and measures the number of hops from the base node. When a node receives the same packet again, it checks the routing depth value again. If the value is smaller than the

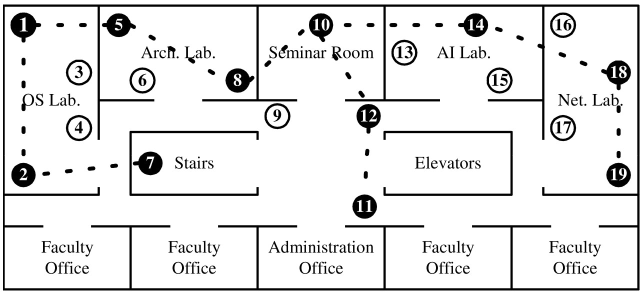


Fig. 1. An example indoor routing path.

current one, it records a shorter routing path. Shortest hop routing is useful for improving the energy and communication efficiency of wireless networks, as sensor nodes have to send sample packets to the base node through several intermediate nodes.

If the nearby nodes 2, 3, and 4 decided to admit the packet, they then have to elect a header node in order to manage the remaining nodes in a power-down mode. We combine distance and battery capacity information in the efficient election of a header node. Approaches based on distance and on battery capacity are described as follows.

In the distance-based approach, nodes 2, 3, and 4 measure the radio signal strengths when they receive a routing packet [16]. If the signal is strong, a node considers the sender node to be close and responds after a long delay; but if the signal is weak, the node responses quickly (see Eq. 1). In this manner, nodes 2, 3, and 4 decide their response times and wait until one of their timers has finished. In this example, the timer of node 2 finishes first because node 2 received the weakest routing packet.

$$Response\_Time \propto Singal\_Strength \tag{1}$$

When the response timer finishes, the node forwards the routing packet to all its neighbor nodes by controlling the signal strength in the same way as the base node did. The routing depth value in the forwarded packet is increased by one. When nodes 3 and 4 receive the forwarded packet, they stop their timers because they know that the node 2 has been elected as a local header node. Then they turn their power off until the next routing period starts. But when node 7 receives the forwarded packet, it repeats a similar procedure and elects a header from local nodes as nodes 2, 3, and 4 did.

After a sufficiently long time interval has elapsed since a node first broadcasts a routing packet, the node rebroadcasts the same packet, but using the maximum radio signal strength so that it can make a path to sensor nodes that are a long way off. If the base node 1 rebroadcasts the routing packet in this way, node 5 can receive it. If node 5 receives the packet, it repeats the already described procedure of electing a header node and forwarding the packet to its neighbors. Since the distances between the header nodes are similar to the routing radius, this approach can build the required spatial similarity aware routing path.

In wireless sensor networks, all sensor nodes should be loaded uniformly. Otherwise, some sensor nodes rapidly dissipate their battery energy, and this fatally degrades the efficiency of the network as a whole. In the election of header nodes, an approach based on battery capacity is therefore developed that uses Eq. 2 to calculate the response time. If a node has a low battery, it uses a long response time to avoid being elected as a header node. Thus a node with more energy left will be more frequently elected as a header node because it responds quickly. As base nodes periodically reestablish the routing path in order to deal with changes in the state of the network, this approach promotes the uniform use of battery energy of all sensor nodes.

$$Response\_Time \propto \frac{1}{Battery\_Capacity} \tag{2}$$

Finally, we combine the distance-based approach and the battery-capacity-based approach in Eq. 3, where $0 \leq \alpha \leq 1$. If the parameter α is close to 0, then the routing path favors the uniform use of sensor nodes energy. But if the parameter is close to 1, the path is build to exploit spatial similarity. Thus, if the parameter is correctly selected, this hybrid approach will turn off the power of geographically adjacent sensor nodes while ensuring uniform energy usage. In this paper, we assume the value of the parameter α to be 0.5.

$$Response\_Time \propto \begin{cases} \alpha \times Normalized\_Signal\_Strength \\ +(1-\alpha) \times (1 - Normalized\_Battery\_Capacity) \end{cases} \tag{3}$$

When a routing path has been established, the header nodes report their sensing results to the base node. An interpolation procedure [11] is then used to reproduce the data from nodes that are turned off. However, the geographical locations of the header nodes are required to reconstruct the data field in a precise manner. We can use one of several location detection methods [15, 16] in partial cooperation with the proposed routing method. We can reduce the number of reports by the header nodes by exploiting the temporal similarity of the data, if the data transport is reliable. We present a reporting method based on temporal similarity in Section 2.2.

2.2 Temporal similarity based reporting method

Radio devices used in a wireless sensor network have a high bit error rate of about 0.5% [6]. Thus, a large proportion of packets are not correctly delivered to the base node, especially when the network diameter is large. If the average packet error rate is E and the hop count is H, the successful packet delivery rate is $(1-E)^H$. For example, if the packet error rate is 30% and the hop count is three, the successful delivery rate is less than 25%.

Due to this low delivery rate, an unreliable radio channel is not energy-efficient. First, there is the delivery failure problem. If a packet makes several hops but is then lost due to an error before it gets to the base node, the energy already used has been wasted. Second, there is the periodic reporting problem. As the channel is unreliable, a sensor node does not know whether previously reported data has been delivered to the base node or not. Thus, even though the new data value is the same as the previously reported one, the sensor node has to report it. The use of unreliable channels in current networks can only be justified by their simplicity.

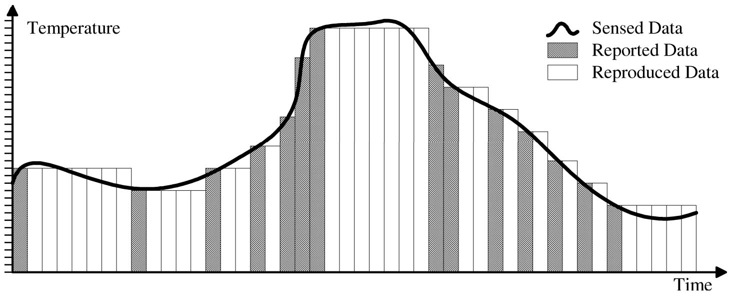


Fig. 2. A temperature sample data of a summer day.

To address the problem of inefficient communications, we use a reliable transport over the unreliable radio channel and a novel reporting method that exploits the temporal similarity of sensing data. This solves the delivery failure problem. Furthermore, our reporting method allows sensor nodes to omit data which are similar to the most recently reported data. The base node recognizes the significance of omitted data and can reconstruct it. Thus, the periodic reporting problem is also solved.

Temporal similarity is observed in many kinds of data, such as temperature, humidity, sound, solar radiation, and so on, as shown in Figure 2 where temperature samples were sensed on a summer day. A sensor node senses physical temperature data (a bold line) periodically and reports the data (gray bars) only when the data value is sufficiently different from the previously reported data value. We call the difference as the quantization degree, and it is specified by the users, depending on the data type. In this example, it is assumed to be $3°C$. Even though the sensor node has reported only about 30% of the sensed data, the base node can reproduce the original data (white bars) by using an interpolation method [11]. In the figure, we use a simple stair interpolation method, and the difference between the interpolated data and the original data is at most $3°C$, which is the specified quantization degree. Thus, the proposed reporting method achieves the required accuracy, while reducing the time and energy needed for communication significantly.

Reliable data transport is typically expensive to implement, and several more energy-efficient transport methods [7, 9, 10] have been studied for wireless sensor networks. Based on these methods, we optimize the selective-repeat ARQ approach [8] to reduce energy consumption and communication time.

3 Evaluation Methodology

This section describes the performance evaluation methodology of the proposed routing and reporting methods compared with the conventional methods. In order to study the performance of various methods accurately, we have developed a byte-level sensor network simulator using Java. The simulator includes various types of sensor nodes that have been modeled as finite-state machines with software timers and job queues. The simulator core divides the simulation time

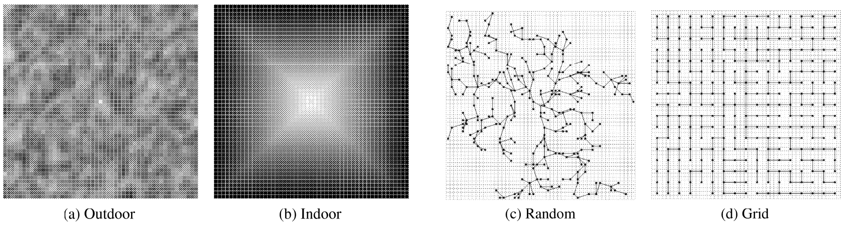

(a) Outdoor (b) Indoor (c) Random (d) Grid

Fig. 3. Error condition maps and examples of sensor dissemination topologies

into intervals that correspond to the transmission of one byte, and schedules all sensor nodes in every time interval.

The simulator provides two error maps, as shown in Figure 3(a) and 3(b). The maps consist of a fifty-one by fifty-one matrix of small cells whose extent is $25m^2$. The cell color corresponds to the medium error rate, and the darker the color the higher the error rate. We assume the average bit error rate to be 0.5% and the error rate range to be between 0% and 1% [6]. We calculate the bit error rate between two sensor nodes by using the average value of their individual bit error rates. Figure 3(a) shows an error map for sensors placed outdoors, and Figure 3(b) shows a map for sensors indoors, where cells close to walls have a high bit error rate because of the interference of the walls. The simulator supports two sensor node dissemination topologies, random and grid, as shown in Figure 3(c) and 3(d). In these topologies, a base node is placed in the center of each map. We used these dissemination topologies in combination with the error maps in every experiment, and calculate the average value.

We selected the hardware parameters of a radio device based on Mote [2, 17]. We set the radio bandwidth to be 40kbps, the communication radius to be 30 meters, and the power consumption of radio device to be 5A in idle state, 4.5mA in either listen or receive state, and 12mA in transfer state. We assumed that the processing time for a data packet and an acknowledgement (ACK) packet to be 10ms and 2ms, respectively. We selected the size of a routing packet, a reporting packet header, and a reporting packet body as twelve, eight, and six bytes, respectively.

4 Performance Evaluation

In this section, we evaluate results from the proposed routing, reporting, and reliable transport methods. First, we optimize a reliable transport method based on a selective-repeat ARQ [8], so as to reduce energy dissipation and improve delivery speed. In this experiment, we assumed the retransmission time of ARQ to be 30-60ms, depending on the packet error rate. We also assumed that the transmission interval is longer than the round-trip time for a packet. In the simulator all sensor nodes treat the ACK packet as their highest priority task, and so this setting can eliminate useless retransmission operations.

Table 1 summarizes our results. Here, reported data means the number of data item that are successfully delivered to the base node, energy means the average power consumption of the radio devices of all sensor nodes, and time

Table 1. Performance of the proposed reliable data transport.

MAC	Spec.	Reported Data	Energy (µJ)		Time (ms)	
			Total	Per Data	Total	Per Data
Stop and Wait ARQ	U=1	184	1,648	9.0	12,730	69
	U=2	184	1,554	8.4	10,352	56
	U=3	184	1,778	9.7	11,340	62
Selective-Repeat ARQ (U=2)	B=4	184	1,344	7.3	8,199	45
	B=6	184	1,294	7.0	8,188	45
	B=8	184	1,375	7.5	8,984	49
Unreliable	R=0	7	134	19.1	223	32

* U: Packet unification count, B: Buffer size in packets, R: Retransmission count.

means the simulation time that elapsed before all data were delivered to the base node.

As the packet error rate is extremely high in wireless sensor networks, we use a packet unification technique where several packets are unified into a single packet in router nodes to reduce the packet header size. This is feasible because the packet body contains all the information about the sample data [18, 19]. The results show that the unification technique performs best when the unification parameter is set to two packets. Based on this, we optimize the buffer size of the selective-repeat ARQ. The results show that the selective-repeat ARQ performs best when the buffer size of both the sender and the receiver is set to six packets. When the buffer size is larger than six packets, performance is degraded due to network congestion and packet collisions. The results show that the optimized ARQ reduces the communication energy per data item by 73%, when compared with an unreliable channel. This is mainly because reliable transport by optimized ARQ addresses the delivery failure problem.

Second, the proposed routing method is compared with a typical shortest-hop routing method. Table 2 shows the fraction of sensor nodes included in a routing path as a function of the routing radius. It shows that, in the typical method, entire sensor nodes are routed regardless of their geographical location. In the proposed method, the fraction of nodes needed for routing is gradually decreased as the routing radius is decreased from 15m to 30m, because a longer routing radius implies a strong spatial similarity. We also observed that, when the routing radius is too short (˜10m) the fraction of nodes needed for routing is also decreased as the packets are not efficiently broadcast. In summary, the proposed routing method can turn off about 28-66% of the nodes, depending on the radius specified to determine desired spatial similarity.

Table 2. Routing radius vs. fraction of header nodes.

Method	Routing Radius	Outdoor		Indoor		AVG
		Random	Grid	Random	Grid	
Proposed Routing	10m	57%	72%	39%	67%	59%
	15m	65%	67%	62%	67%	65%
	20m	57%	54%	59%	55%	56%
	25m	43%	48%	50%	48%	47%
	30m	34%	35%	43%	38%	38%
Typical	30m	100%	100%	100%	100%	100%

Figures 4(a) and 4(b) show the sensing density of the header nodes in the proposed and typical routing methods, respectively. We have assumed that users want to sense up to 3 samples in any 20m radius zone, and so light gray, gray, and dark gray cells correspond to an appropriate sensing density, an over sensing density, and an excessive sensing density (1-3, 4-6, and over 6 samples per the zone). Figure 4(b) shows that, since the users cannot specify the sensing density in the typical method, it wastes valuable energy resources due to the excessively long routes to all sensor nodes. Moreover, in the typical method, the sensing density is not uniformly distributed over the whole network area. But the proposed method satisfies the required sensing density throughout the area covered by the network, as shown in Figure 4(a), while turning off the power in many nodes.

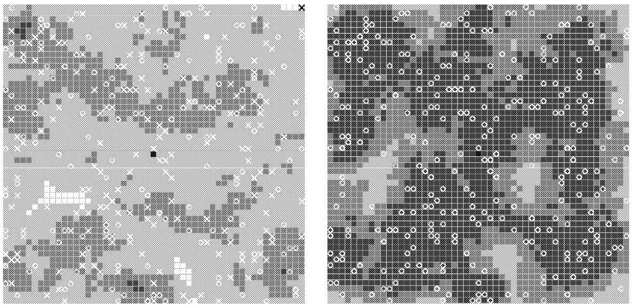

(a) Proposed (b) Typical

Fig. 4. Sensing Density of Routed Nodes.

Figure 5 shows the remaining battery capacity of all sensor nodes for the proposed and typical methods. A brighter color corresponds to a higher battery capacity. The results show that the typical method wastes the sensors batteries more quickly than the proposed method. Thus, we see that some intermediate router nodes waste their battery capacity faster since they have to forward several packets from the child nodes to the parent node. As indicated by the dotted lines, the average battery life for all sensor nodes is extended by over 230%. And when the parameter α is close to 0, the battery capacity of all sensor nodes is more uniformly used.

Third, we evaluated the proposed reporting method against a typical periodic

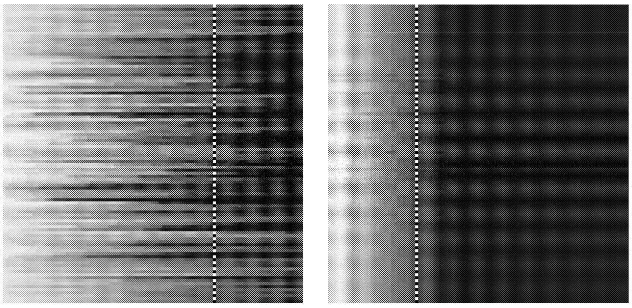

(a) Proposed (b) Typical

Fig. 5. Remaining battery capacity of all sensor nodes (y-axis) against time (x-axis).

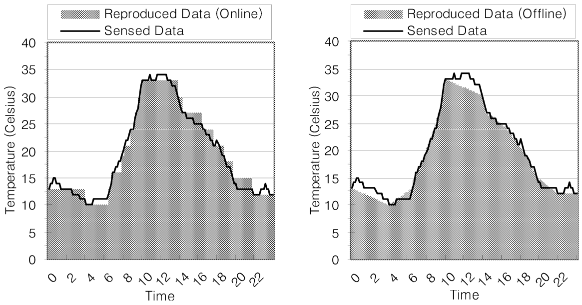
Table 3. The fraction of reported data item (R) and the sensing accuracy (A) as a function of the quantization degree (QD).

Temperature			Humidity			Solar Radiation		
QD	***R***	***A***	***QD***	***R***	***A***	***QD***	***R***	***A***
0℃	100%	100%	0%	100%	100%	0Lux	100%	100%
1℃	58%	100%	1%	38%	100%	10Lux	15%	100%
2℃	28%	97%	5%	17%	98%	50Lux	14%	99%
3℃	16%	94%	10%	6%	96%	100Lux	11%	99%
5℃	9%	91%	20%	3%	92%	200Lux	8%	99%
10℃	5%	86%	50%	2%	80%	500Lux	4%	98%

reporting method. In this experiment, we used the temperature, humidity, and solar radiation data sensed by five sensor nodes, every 10 minutes on a summer day at Great Duck Island [12]. Table 3 shows the fraction of sensed data being reported (R) and the sensing accuracy (A), as a function of the quantization degree (QD). We define the sensing accuracy in Eq. 4, where $R(i)$ refers to the data reproduced by interpolation, $S(i)$ refers to the originally sensed data, and N is the number of sensed data points. The results show that the proposed method reduces the number of reports by 72%, 94%, and 96% for temperature, humidity, and solar radiation, respectively, while degrading the sensing accuracy by less than 5%. These large reductions are mainly due to the fact that the sensed data have storing temporal similarity and tend to change in a predictable manner. In this experiment, a stair interpolation is used to reconstruct the originally sensed data.

$$Sensing\_Accuracy = 1 - \frac{1}{N}\sum_{i=1}^{N}\frac{\mid \mid R(i) \mid - \mid S(i) \mid \mid}{\mid S(i) \mid} \qquad (4)$$

We have used two interpolation methods, stair and linear. The stair method predicts that the omitted sample data value is equal to the previously reported data value, and the linear method predicts that the omitted data value can be reconstructed from the value between two reported data points that span the omitted point. The linear method can only be used for off-line analysis, while the stair method can be used both on-line and off-line. Figure 6 shows that these two methods accurately reproduce the original sensing data even though 84% of sensed data values are omitted.



(a) Linear Interpolation (b) Stair Interpolation

Fig. 6. Data reconstructed using two interpolation methods, with a quantization degree of $3^\circ C$ and a reporting rate of 16%.

In summary, these experimental results show that our proposed routing method can turn off 28-66% of all the sensors, and the proposed reporting method can reduce the radio energy consumption of each header node by 72-96% with degradation in the sensing accuracy of less than 5%. Therefore, the proposed data similarity aware routing and reporting scheme can reduce the communication energy for reporting operations by an order of magnitude when compared with a full routing and reporting scheme.

5 Related Work

In wireless sensor networks, users are usually interested in reliable collective information from the sensors, not in their individual results. Many nodes can be spatially and temporally turned off in order to reduce the communication energy without harming sensing accuracy. But no existing scheme ensures the quality of reported data by exploiting similarities in the data.

TAG [20] provides an in-network aggregation technique in which statistical data (e.g. min, max, and average value) are obtained from many samples during routing. As TAG cannot control the reporting rate, partially reliable transport methods such as DRT [9] and ESRT [10] have been developed. These can ensure that a specified fraction of the sensing data is correctly delivered to a base node in either a decentralized or a centralized manner. However, these transport methods do not exploit the data similarities. Even when sensed data are quite similar, they are still redundantly reported.

Although there are various routing algorithms for ad-hoc sensor networks that use location information, so far as we know, none of the existing algorithms have been developed with the aim of exploiting the spatial and temporal similarity of the sensed data with subsequent interpolation [1, 21, 22, 23].

6 Conclusions

In this paper, we have presented an energy-efficient routing and reporting scheme by exploiting spatial and temporal data similarities in wireless sensor networks. The proposed routing method intelligently excludes several adjacent sensor nodes from the routing path, and the proposed reporting method omits data when new values are similar to previous ones. Because sensor nodes use a reliable data transmission method, the proposed scheme reproduces the originally sensed data accurately by interpolation. Experimental results show that the proposed scheme can reduce the communication energy for data reporting by an order of magnitude with only a slight reduction in sensing accuracy.

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