E-DSR: Energy-efficient Routing for Sensors with Diverse Sensing Rates

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Abstract—Cluster-based routing is popularly used in *wireless sensor networks (WSNs)*, where sensors are organized into clusters and *cluster heads (CHs)* are selected to compress and forward packets for other nodes. However, most of existing protocols implicitly assume that sensors produce data with the same speed. Due to event occurrence or application needs, sensors may have different sensing rates in practice. Some CHs may thus encounter serious buffer overflow and dispose of many packets. To conquer this problem, the paper proposes a protocol called *Energy-efficient routing for sensors with Diverse Sensing Rates (E-DSR)* to extend network lifetime and diminish lost packets. E-DSR divides the network into grids and selects one CH in each grid based on multiple factors such as its position, residual energy, and sensing rate, so as to improve energy efficiency on routing. Moreover, depending on traffic loads of CHs, E-DSR adaptively splits or merges grids to avoid buffer overflow or facilitate data compression, respectively. Simulation results verify that E-DSR significantly prolongs network lifetime and reduces the data loss rate, as compared with various routing protocols developed for WSNs.

Index Terms—cluster, energy efficiency, routing protocol, sensing rate, wireless sensor network.

1 Introduction

Owing to the gradual rise of Internet of Things (IoT), *wireless sensor network (WSN)* is playing an increasingly important role in both industry and people's livelihood [1]. A WSN is composed of numerous sensors deployed in the region of interest to facilitate getting environmental information. Each sensor is a small but self-reliant device which keeps monitoring the surroundings and regularly reports its observations (called *sensing data*) to a sink. Many WSN applications have been also developed, from intelligent transportation [2] to precision agriculture [3], air-pollution monitoring [4], personal health-care [5], and smart shopping [6].

Since sensors are usually powered by small batteries and replacing their batteries is not economic, how to save energy of sensors to extend network lifetime is critical. Generally speaking, a sensor spends most of its energy on communications [7]. In a large-scale WSN, lots of sensors rely on multihop transmissions to report sensing data to the sink. Except for leaf sensors, all other sensors have to relay packets for their neighbors farther from the sink. It is predicable that a sensor closer to the sink will relay more data and consume much more energy. Thus, some sensors may quickly run out of energy and the WSN will be in danger of partition. This problem is known as the *energy hole problem* [8].

Various strategies can be adopted to solve the energy hole problem, for example, applying the sleep mechanism to turn off the transceivers of sensors [9] or using mobile sinks to visit sensors and gather their sensing data [10]. This paper aims to cope with the problem by improving packet routing in WSNs. Specifically, we consider cluster-based routing protocols, where sensors are arranged into clusters such that the sensors of the same cluster will be located in close proximity. In each cluster, a special node called *cluster head (CH)* is selected to collect the sensing data from other sensors in the cluster and relay these data to the sink.

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Cluster-based routing protocols have three potential benefits as compared with flat ones:

- *Load balance:* In flat routing protocols, each sensor partakes in the routing mission. Thus, the sensors located on popular paths (e.g., the shortest paths) would have to relay many packets originated from the majority of nodes, which burdens them with heavy loads. On the contrary, only CHs involve in packet routing in cluster-based routing protocols. Since sensors can take turns acting as CHs, their loads will be balanced accordingly.
- *Data compression:* In each cluster, traffic flows will converge on a CH, so it is easy for the CH to adopt the data compression mechanism to integrate and condense the collected data [11]. Though the same mechanism can be applied to flat routing protocols, the performance of data compression may not be as good as that of cluster-based ones because traffic flows would be relatively diverge.
- *Energy hole:* Through properly rotating the role of CH and compressing sensing data, a cluster-based routing protocol can prevent the sensors close to the sink from relaying a large number of packets. Thus, the problem of energy hole can be alleviated, in contrast with flat routing protocols.

Nevertheless, most of cluster-based routing protocols implicitly assume that sensors produce sensing data with the same speed (i.e., their sensing rates are equal) and they also have large enough buffers to store data. These two assumptions are not always available in practice. Specifically, some sensors will be asked to raise sensing rates when they detect interested events [12]. Moreover, sensors usually possess limited memory space to cache data [13]. Diverse sensing rates bring about two negative effects on cluster-based routing protocols. First, when parts of sensors in a cluster increase sensing rates, they could transmit an amount of data that exceed the size of the CH's buffer, which forces it to abandon some packets because of buffer overflow. Second, the sensors with high sensing rates may be also chosen as CHs (e.g., they

have shorter distances to the sink or more residual energy). In this case, they will be imposed with a heavy workload (i.e., frequently sensing and also relaying data), thereby accelerating depletion of their energy.

To address these issues, we propose a protocol called *Energy-efficient routing for sensors with Diverse Sensing Rates (E-DSR)* with the objective of extending network lifetime and cutting down on data loss caused by buffer overflow. Specifically, E-DSR maintains a dynamic grid structure to manage the network, where grids correspond to clusters. In every grid, one CH is carefully selected by taking account of the positions, residual energy, and also sensing rates of sensors, so as to save their energy expense on communications in the grid. Then, instead of directly transmitting data to the next-hop CH, each CH may choose a forwarding node in the neighboring grid if this node possesses better conditions on relaying data than its CH. Moreover, we apply priority queues to the buffer management for CHs and forwarding nodes to distinguish encapsulated packets from uncompressed ones, so as to alleviate the impact of data loss in case of buffer overflow. During network operation, some grids would be further divided into subgrids once their CHs find that too many packets of sensing data are produced in the grids, so as to curtail the frequency of occurrence of buffer overflow. In case that the sensing rates of these sensors are back to normal, the subgrids can be merged to enhance the efficiency of data compression. Through extensive simulations, we show that the proposed E-DSR protocol can substantially extend network lifetime, conserve more energy of sensors, and also decrease the data loss rate, as compared with other routing protocols.

This paper is outlined as follows: Section 2 surveys related work and Section 3 defines the routing problem. After that, we detail the design of E-DSR in Section 4, followed by performance evaluation in Section 5. Finally, Section 6 draws a conclusion and gives future work.

2 Related Work

There have been a variety of routing protocols proposed for WSNs. Depending on their routing philosophy, most of them can be classified into *flat* and *cluster-based* ones. Below, we survey these two categories of protocols.

2.1 Flat Routing Protocols

As for flat routing, AODV (ad hoc on-demand distance vector) [14] is commonly used in both ad hoc networks and WSNs, where nodes find the shortest paths to their destinations by exchanging route requests (RREQs) and route replies (RREPs). Many protocols based on AODV are also developed to raise energy efficiency in routing. CAODV (cross-layer AODV) [15] decreases the overhead of route discovery by restricting one-hop neighbors to receive RREQs. To do so, a back-off timer is set at the MAC (medium access control) layer for each sensor to check whether to drop RREQs. In AODV-LB (AODV load balancing) [16], if a sensor has a heavy workload or low energy, it does not partake in routing and discard RREQs accordingly. Since AODV modifies a route only when it is broken, the study [17] considers shortening the route whenever the topology changes (e.g., some sensors are moved), even if the route is still available. To provide stable routes, the work [18] lets sensors estimate received signal strength of RREQs. Only when the signal strength overtakes a threshold, will the sensor agree to forward packets. In [19], sensors add the values of their energy in RREQs, and the routing path whose energy level is the highest will be chosen. EA-AODV (energy-aware AODV) [20] also limits sensors to be part of the routing process based on their received signal strength of RREQs. Then, it selects a shorter path whose sensors possess the most energy to do the routing job.

Several protocols aim to reduce the message cost for sensors to relay data. MCF (minimum cost forwarding) [21] asks each sensor to estimate its cost (e.g., hop count) to forward packets to the sink. When a sensor gets one new packet, it transmits the packet to a neighbor if it is on the minimum-cost path to the sink. Supposing that the positions of all sensors are known, GCF (geographic collaborative forwarding) [22] makes each sensor choose a neighbor closest to the sink to forward its packets. Given a WSN with multiple sinks, GBR (gradient-based routing) [23] finds the gradient of each link, which is the difference between hop-counts to the nearest sink of its two endpoint sensors. Then, each sensor picks a link with the maximum gradient to send packets.

To balance energy consumption of sensors on routing, a number of protocols consider their remaining energy. The work [24] asks every sensor to check if its energy is enough to send packets whenever it gets an RREQ. If so, the RREQ is rebroadcasted, or discarded otherwise. For a pair of source and target sensors, the study [25] computes the transmission cost in energy via each relay node. Then, the one with the minimum cost is selected to forward packets from the source to the target. REBM (residual energy based multipath routing protocol) [26] selects a relay node for each sensor by three rules: 1) the node with the maximum energy, 2) the node closest to the sender, and 3) the node that has the fewest children. In [27], each sensor records trust values for its neighbors based on the packet delivery ratio, energy consumption, and acknowledgement success/failure counts. Then, the sensor chooses a neighbor with the largest trust value to relay its packets.

In the above protocols, all sensors are assigned equal roles on forwarding packets. As discussed in Section 1, they may be vulnerable to the energy hole problem. In particular, since all nodes are static, the sensors near to the sink will relay much more packets than others. This phenomenon leads to non-uniform energy consumption of sensors, making those sensors adjacent to the sink fast run out of their energy [28]. In this case, the sink would soon become disconnected from all other sensors, thereby shortening network lifetime.

2.2 Cluster-based Routing Protocols

LEACH (low energy adaptive clustering hierarchy) [29] is a typical example in such protocols. To choose CHs, every sensor decides a probability p_i. When p_i overtakes threshold $T(i)$, the sensor claims to be a CH and then nearby sensors join its cluster. Since LEACH considers merely the density of CHs, a variety of protocols are thus developed to improve it. I-LEACH (improved LEACH) [30] includes the amount of residual energy, the number of neighboring nodes, and the distance to the sink of each sensor in the calculation of $T(i)$. EC-LEACH (enhanced centralized LEACH) [31] also considers residual energy of sensors. It iteratively selects one CH based on the largest unused $T(i)$ value, such that any two CHs are not close to each other. In FT-LEACH (fault-tolerant LEACH) [32], each sensor notifies the CH of its residual energy (via packet headers) and does not send similar data to the CH in

TABLE 1: Comparison between the prior cluster-based routing protocols and our E-DSR protocol.

routing protocols	network structure	CH selection	sensor position	residual energy	sensing rate	buffer overflow
LEACH [29]	non-specific	probabilistic				
I-LEACH [30]	non-specific	probabilistic	√	√		
EC-LEACH [31]	non-specific	probabilistic	√	√		
FT-LEACH [32]	non-specific	probabilistic		√		
IB-LEACH [33]	non-specific	probabilistic				
VC-LEACH [34]	non-specific	probabilistic		√		
EMOD-LEACH [35]	non-specific	probabilistic				
LEACH-MAC [36]	non-specific	probabilistic				
EHA-LEACH [37]	non-specific	probabilistic		√	√	
SCT [38]	ring	deterministic	√			
BACR [39]	ring	probabilistic	√	√		
EBUCP [40]	ring	probabilistic		√		
EBDRA [41]	non-specific	deterministic		√		
ERA [42]	non-specific	deterministic		√		
NRCA [43]	grid	deterministic	√	√		
our E-DSR protocol	grid	deterministic	√	√	√	√

two successive rounds. Thus, the CH knows who are alive in its cluster and sensors can avoid sending duplicate data to save energy. IB-LEACH (intra-balanced LEACH) [33] reduces the communication cost in a cluster and the CH's load by sharing the routing job among the CH and other sensors. VC-LEACH (vice cluster LEACH) [34] picks a sensor (except for the CH) with the most residual energy to be a vice CH. Once the original CH dies, this vice CH can immediately take over its job. EMOD-LEACH (enhanced modified LEACH) [35] adopts dual levels of transmitted power, where low-level power is used for intra-cluster communications and high-level power is used for inter-cluster ones. LEACH-MAC (LEACH with MAC) [36] finds the optimal number of CHs and adds random time for sensors to broadcast CH advertisements, so as to make the number of selected CHs close to the optimal value. EHA-LEACH (energy harvested aware LEACH) [37] uses an energy potential function to calculate $T(i)$, which considers the mean and variance of residual energy of sensors in a near future.

Few studies organize the WSN into a ring structure. Given a circular WSN centered at the sink, SCT (spatial correlation-aware tree) [38] splits it into concentric rings of an equal width. Each ring is cut into sectors such that the number of sensors in each sector is similar. Then, one CH is picked in a sector, and each CH sends data to the sink via the closest CH in the next inner ring. In BACR (backoff announcement and cluster reappointment) [39], each sensor decides a probability to act as the CH based on its ring number, the region's area, and the expected ratio of CHs. Afterwards, the sensor announces its energy to neighbors, and gets one vote if it has more energy than a neighbor. If multiple sensors compete for the CH role, the one that gets the most votes wins. Assuming that the sink located at the center of a WSN, EBUCP (energy-balanced unequal clustering protocol) [40] divides it into three rings, where nodes in the most inner ring directly send data to the sink. After that, sensors are categorized into normal, advanced, and super ones, where super sensors have more initial energy, followed by advanced and normal sensors. Each type of sensors are given with a different formula to find their probabilities to act as CHs, where super sensors will have the highest priority.

Supposing that the amount of energy consumption on sending data is fixed, EBDRA (energy balanced dynamic cluster routing approach) [41] selects those sensors with more energy than neighbors to be CHs. Then, each CH always picks the neighboring CH with the most energy to relay packets. In ERA (energy-aware routing algorithm) [42], each sensor initiates a timer for the campaign of CH selection, which depends on its residual energy. After that, a virtual backbone to connect all CHs and the sink is built for the routing purpose. NRCA (node ranking clustering algorithm) [43] maintains a grid structure to cluster sensors. In each grid, a sensor that possesses the most energy will be the CH. In case of a tie, the sensor closest to the sink will be the winner.

Table 1 gives a comparison between the prior cluster-based routing protocols and our E-DSR protocol. Some of them consider positions or residual energy of sensors when selecting CHs to raise energy efficiency. Only EHA-LEACH takes sensing rates into account, which are used to predict the future energy of sensors. As compared with these protocols, E-DSR ponders more factors including positions, residual energy, and sensing rates of sensors. Furthermore, E-DSR mitigates buffer overflow occurred at CHs to improve reliability on data transmissions. This issue is not addressed in the above protocols.

3 Problem Formulation

In this section, we give the network architecture, followed by the energy consumption model of sensors. Afterwards, we present the routing problem in WSNs.

3.1 Network Architecture

Let us consider a set of static sensors randomly deployed in the sensing field to gather environmental information to be sent to the sink. Sensors are homogeneous, in the sense that they have the same battery capacity E (i.e., initial energy), maximum communication range r_c, and buffer size. In particular, a sensor can store at most B packets of sensing data in its buffer. If the buffer is full but new packets are produced by or sent to the sensor, buffer overflow occurs and these packets are discarded.

However, each sensor s_i may have a different *sensing rate* R_i, which is defined by the reciprocal of the interval between two successive packets of sensing data produced by s_i. For example, if s_i produces one packet every 360 seconds, its sensing rate is $R_i = 1/360$. The sensing rate could dynamically change during network operation. In particular, s_i will be asked to raise R_i once it detects an abnormal event and then restore R_i to the default value after the event disappears.

Below, we make several assumptions about the WSN. First, sensors know their positions, which can be carried out by some

localization techniques [44]. Second, sensors are capable of adjusting their transmitted power. This assumption is widely considered in many energy-efficient mechanisms to extend WSN lifetime [45]. Third, sensors can piggyback information of residual energy and sensing rates on the packets of sensing data to be sent to CHs, so they are aware of the status of each member. Finally, after a CH collects packets from other sensors, the CH employs a data compression algorithm to condense these packets (whose compression ratio is λ, where $0 < \lambda < 1$) and then sends out one compressed packet. However, compressed packets cannot be further condensed.

3.2 Energy Consumption Model

Sensors consume energy on producing, transmitting, and receiving packets. To assess the amount of energy spent by these operations, we adopt the model in [46]. Suppose that a sensor s_i produces one packet of sensing data with b bits. Then, s_i has to spend an amount of energy:

$$E_{\mathrm{Se}}(s_i) = (V_{\mathrm{Se}} \times A_{\mathrm{Se}} \times T_{\mathrm{Se}}) \times b, \tag{1}$$

where V_{Se}, A_{Se}, and T_{Se} are the voltage, electric current, and time required by the sensing unit of s_i to produce the packet, which are measured in volts, amperes, and seconds, respectively. If s_i sends the packet to its one-hop neighbor s_j, s_i will consume an amount of energy:

$$E_{\mathrm{Tx}}(s_i, s_j) = (\xi_1 + \xi_2 \times d^{\varepsilon}(s_i, s_j)) \times b, \tag{2}$$

where ξ_1 and ξ_2 indicate the amount of power taken by s_i's transmitter and amplifier circuits to send out one bit, respectively, and $d(s_i, s_j)$ is the Euclidean distance between s_i and s_j. In Eq. (2), the exponent ε is usually set to 2 or 4 to imitate the power-loss effect for free space or multipath fading, respectively. Besides, s_j also spends energy to receive the packet, which is calculated by

$$E_{\mathrm{Rx}}(s_j, s_i) = \xi_3 \times b, \tag{3}$$

where ξ_3 is the amount of power that s_j's receiver circuit spends to get one bit.

3.3 The Routing Problem

Given a WSN mentioned in Section 3.1, our problem asks how to select CHs from sensors and decide routing paths to relay sensing data to the sink, such that 1) network lifetime is maximized and 2) data loss is reduced. Here, network lifetime is defined by the time span since the WSN starts operating until the first sensor uses up its energy. Moreover, the data loss rate ρ is defined by

$$\rho = \frac{M_p - M_s}{M_p}, \tag{4}$$

where M_p is the amount of sensing data produced by all sensors and M_s is the amount of sensing data sent to the sink successfully. In case of using data compression, the sink will decompress the received packets, so we consider the amount of uncompressed sensing data gotten by the sink for M_s. Moreover, transmission failure (i.e., packet collision) and buffer overflow will lead to packet discard and cause data loss. As packet collision is chiefly handled by the MAC layer [47], in the paper we target to decrease buffer overflow occurred at CHs.

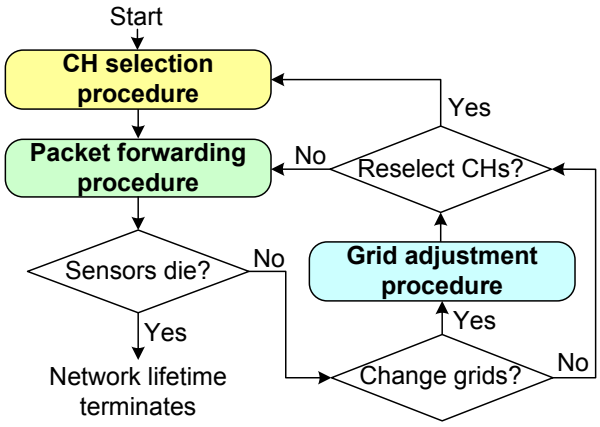


Fig. 1: Flowchart of the E-DSR protocol.

4 The Proposed E-DSR Protocol

Suppose that sensors are deployed in a rectangular region and the sink is placed at one of its corners. The region is initially partitioned into $G_W \times G_H$ *basic grids* to cluster sensors, where $G_W, G_H \in \mathbb{N}$ and $\max\{G_W, G_H\} \geq 2$. In other words, there should be at least 2×1 basic grids. Each basic grid may be further divided into subgrids if necessary, but neighboring basic grids cannot be merged together. Both the values of G_W and G_H depend on the region's size and the maximum communication range r_c of sensors. Let l_G be the grid length. Then, the following condition should be met:

$$r_c \geq \sqrt{l_G^2 + l_G^2} \Rightarrow l_G \leq \sqrt{r_c^2/2}. \tag{5}$$

Here, Eq. (5) makes sure that any two sensors in a grid can directly talk with each other. Besides, for each packet of sensing data, its final destination must be the sink.

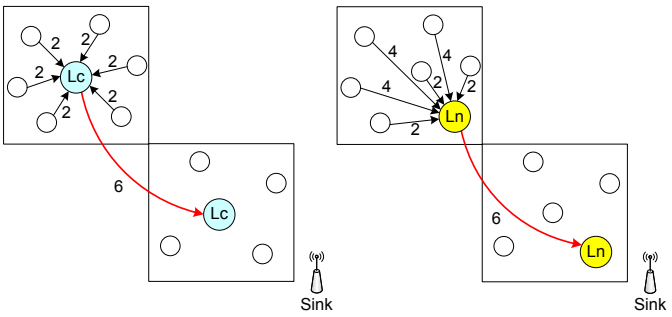
Fig. 1 presents the flowchart of the E-DSR protocol. The *CH selection procedure* is first used to decide CHs for all grids. Then, each CH keeps collecting, compressing, and routing packets for other sensors in its grid according to the *packet forwarding procedure*. By the definition in Section 3.3, network lifetime terminates when any sensor uses up its energy. Otherwise, we check if some grids need to be altered based on traffic loads of their CHs. If so, the *grid adjustment procedure* is invoked to divide or merge grids. To balance energy expense of sensors, the CHs of some grids could be reselected. Below, we elaborate on each procedure, followed by a discussion of E-DSR.

4.1 CH Selection Procedure

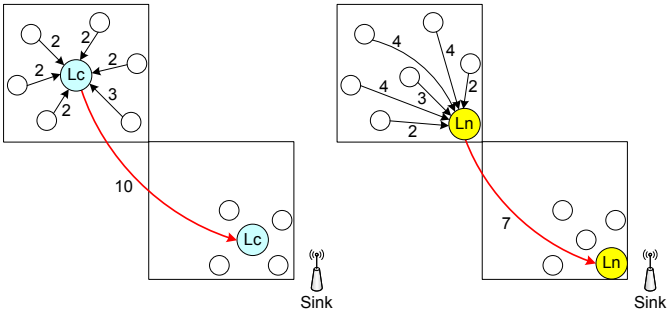
This procedure selects one sensor in each grid to serve as the CH. Generally speaking, there are two good locations for the CH in a grid to save energy of sensors on sending packets. One location (denoted by L_c) is the *geometric center* of all nodes in the grid. Let the grid contain a set $\mathcal{S}$ of sensors. The coordinates of L_c can be calculated by

$$(x_c, y_c) = \left(\sum\nolimits_{\forall s_j \in \mathcal{S}} x_j/|\mathcal{S}|, \sum\nolimits_{\forall s_j \in \mathcal{S}} y_j/|\mathcal{S}| \right), \tag{6}$$

where (x_j, y_j) denote the coordinates of each sensor s_j. If the CH is located at L_c, all other sensors can take the minimum energy to send packets to the CH. The other location (denoted by L_n) is the position of the sensor closest to the sink. When the CH is located at L_n, it can spend the least amount of energy to forward packets to the next-hop CH in an adjacent grid.



(a) Case of choosing L_c



(b) Case of choosing L_n

Fig. 2: Two examples of choosing between L_c and L_n.

To choose between L_c or L_n, we estimate the total amount of energy spent on data transmissions in the grid, including the amount of sensors' energy to transmit packets to the CH and the amount of the CH's energy to relay data to its next hop. Observing from Eq. (2), the amount of energy spent on transmitting data is proportional to the ε-th power of the distance between both the sender and the receiver. Thus, we can simplify the calculation of energy estimation by considering merely distances as follows:

Choosing L_c:

$$\tilde{D}_c = \sum\nolimits_{\forall s_j \in \mathcal{S}} d^{\varepsilon}(s_j, L_c) + \lambda|\mathcal{S}| \times d^{\varepsilon}(L_c, H_c) \quad (7)$$

Choosing L_n:

$$\tilde{D}_n = \sum\nolimits_{\forall s_j \in \mathcal{S}} d^{\varepsilon}(s_j, L_n) + \lambda|\mathcal{S}| \times d^{\varepsilon}(L_n, H_n) \quad (8)$$

In particular, the CH collects $(|\mathcal{S}|-1)$ packets from all members and compresses these packets together with its packet, where λ is the compression ratio. That is why we multiply the second terms in both Eqs. (7) and (8) by a factor of $\lambda|\mathcal{S}|$. Moreover, H_c and H_n are the geometric center and the node closest to the sink in the neighboring grid to which the CH will forward packets, respectively. Fig. 2 illustrates two examples, where $\varepsilon = 2$ and $\lambda = 0.8$. Each number denotes the distance between two nodes. In Fig. 2(a), we have $\tilde{D}_c = 24 + 0.8 \times 7 \times 6^2 = 225.6$ and $\tilde{D}_n = 60 + 0.8 \times 7 \times 6^2 = 261.6$, so L_c is chosen. On the other hand, since $\tilde{D}_c = 589$ and $\tilde{D}_n = 339.4$ in Fig. 2(b), L_n will be thus chosen.

Let L be the location chosen (i.e., $L = L_c$ if $\tilde{D}_c < \tilde{D}_n$, or $L = L_n$ otherwise). One may directly pick the sensor, say, s_p closest to L as the CH. However, this sensor could have less energy. Even worse, its sensing rate may be pretty high. If we simply choose s_p to be the CH, it would accelerate depletion of energy. To address this issue, we also refer to the *expected residual energy (ERE)* of each sensor s_i, which is estimated by

$$E_i^R = E_i - T_{\text{obs}} \times R_i \times E_{\text{Se}}(s_i), \quad (9)$$

where E_i is the amount of s_i's current energy and T_{obs} is the length of an observing period (e.g., T_{obs} is set to 1000 seconds in our simulations). Then, we compute a *weight* $W_i^{\mathbf{H}}$ of each sensor s_i for the CH selection by

$$W_i^{\mathbf{H}} = \alpha \times \left(1 - \frac{d(s_i, L)}{\max_{\forall s_j \in \mathcal{S}} d(s_j, L)}\right) + \frac{\beta E_i^R}{\max_{\forall s_j \in \mathcal{S}} E_j^R}, \quad (10)$$

where $\alpha, \beta \in [0, 1]$ and $\alpha + \beta = 1$. From Eq. (10), a larger $W_i^{\mathbf{H}}$ value implies that s_i is closer to L and has more ERE. Therefore, by selecting the sensor with the largest weight to serve as the CH, not only all sensors in the grid can save their energy on sending data but also the CH has sufficient energy to do the routing job. In Section 5.5, we will investigate the effect of both coefficients α and β on network lifetime and give their suggested values.

4.2 Packet Forwarding Procedure

In each grid, all members directly transmit their packets of sensing data to the CH. After gathering a number of packets (depending on the data compression algorithm [11]), the CH encapsulates them into a single compressed packet to be sent to the sink. To do so, the CH selects one sensor in the next-hop grid to be its *forwarding node*, where the next-hop grid is defined by the neighboring grid (including the diagonal one) closest to the sink.

Let us denote by C_{end} the grid adjacent to the sink. In other words, C_{end} will be the last grid for each routing path. Then, there are two policies to select a forwarding node for each CH h_x.

Policy 1: The next-hop grid is not C_{end}. Let $\mathcal{S}_N$ be the set of sensors in the next-hop grid, whose CH is h_y. If a sensor $s_i \in \mathcal{S}_N$ is selected as the forwarding node, where $s_i \neq h_y$, s_i transmits the compressed packet (sent from CH h_x) to h_y. Similar to the idea in Eqs. (7) and (8), we estimate the amount of energy consumption for h_x to send data to h_y through s_i as follows:

$$\tilde{D}_i = d^{\varepsilon}(h_x, s_i) + d^{\varepsilon}(s_i, h_y). \quad (11)$$

Following the concept in Eq. (10), a weight is associated with each sensor in $\mathcal{S}_N$ for choosing the forwarding node:

$$W_i^{\mathbf{F}} = \alpha \times \left(1 - \frac{\tilde{D}_i}{\max_{\forall s_j \in \mathcal{S}_N} \tilde{D}_j}\right) + \frac{\beta E_i^R}{\max_{\forall s_j \in \mathcal{S}_N} E_j^R}, \quad (12)$$

where the ERE E_i^R is calculated by Eq. (9). Then, the sensor with the maximum $W_i^{\mathbf{F}}$ value is selected as h_x's forwarding node in the next-hop grid.

Policy 2: The next-hop grid is C_{end}. Because the next-hop grid is the last grid to the sink, the forwarding node should directly send h_x's compressed packet to the sink, instead of sending it to h_y. In this way, the routing path is shorten and h_y need not consume extra energy to send h_x's packet. Thus, the estimation of energy consumption in Eq. (11) is modified by

$$\tilde{D}_i = d^{\varepsilon}(h_x, s_i) + d^{\varepsilon}(s_i, \text{sink}). \quad (13)$$

By using Eq. (12), we can calculate the weight $W_i^{\mathbf{F}}$ for each sensor in C_{end} and then pick the one with the largest weight to be h_x's forwarding node.

Fig. 3 presents an example, where grid C_9 is C_{end}. All members in grid C_1 transmit sensing data to their CH. After that, the CH in C_1 sends a compressed packet to the forwarding node s_i in grid C_5. The remaining routing path will be

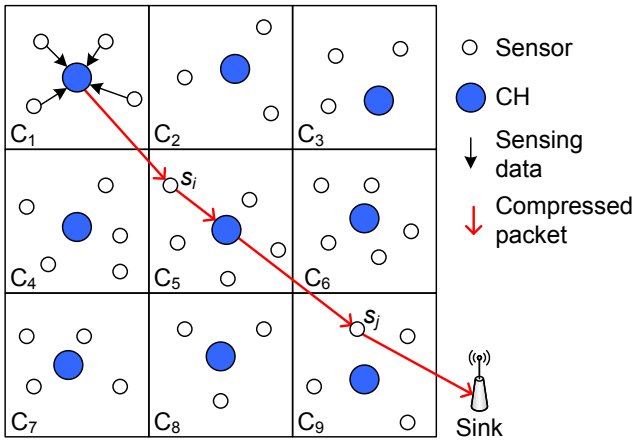


Fig. 3: An example of how the packet forwarding procedure works.

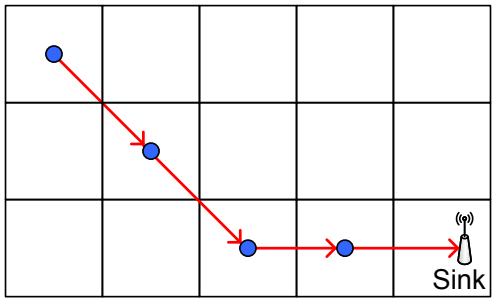


Fig. 4: The longest routing path in terms of grids.

$s_i \rightarrow C_5$'s CH $\rightarrow s_j$ (in C_9) $\rightarrow$ sink. Theorem 1 then analyzes the maximum length of routing paths found by the E-DSR protocol.

Theorem 1. Suppose that a WSN is divided into $G_W \times G_H$ grids. Any routing path in E-DSR has at most $(2 \times \max\{G_W, G_H\} - 1)$ hop counts.

Proof: Without loss of generality, let us assume that the sink is placed at the bottom right grid. Thus, the longest routing path will be originated from a sensor in the upper left grid. This routing path must pass through diagonal grids and then right grids, as shown in Fig. 4. In this case, it passes through no more than $\max\{G_W, G_H\}$ grids. Observing from Fig. 3, the routing path takes at most two hops to pass through each grid, except for the last grid (i.e., C_{end}). Therefore, the total hop counts in the routing path will be $2 \times (\max\{G_W, G_H\} - 1) + 1 = 2 \times \max\{G_W, G_H\} - 1$, which verifies this theorem. □

Because the CH takes charge of the routing mission in a grid, it inevitably consumes more energy than others. To balance energy consumption of all sensors in the grid, they should act as the CH by turns. To do so, whenever a sensor, say, s_k has served as the CH for a predefined time (e.g., 100 seconds), it computes a *reselecting indicator*:

$$\hat{I}_k = \begin{cases} 0 & \text{if } E_k \geq E_{\text{avg}} \\ \frac{E_{\text{avg}} - E_k}{E_{\text{avg}}} & \text{otherwise,} \end{cases} \quad (14)$$

where E_{avg} denotes the average residual energy of sensors in s_k's grid. Then, the condition of Eq. (15) is adopted to check whether s_k should remove the duty of the CH:

$$\hat{I}_k \geq \delta, \quad \text{where } 0 < \delta < 1. \quad (15)$$

In particular, s_k can still serve as the CH if its residual energy E_k is above the average one based on Eqs. (14) and (15). Otherwise, when $\hat{I}_k$ overtakes threshold δ, it implies that s_k's residual energy falls below a $(1-\delta)$ ratio of the average energy. In this case, s_k has spent lots of energy on doing the routing job, so the CH selection procedure in Section 4.1 is invoked to pick another sensor to be the new CH.

When data compression is used, CHs and forwarding nodes may receive heterogeneous packets, which include compressed packets (encapsulated by CHs) and packets of sensing data. In particular, compressed packets should be given precedence over other packets on transmissions, since one compressed packet actually carries an amount of information approximate to $\lfloor 1/\lambda \rfloor$ packets of sensing data. In other words, if a compressed packet is dropped (due to buffer overflow), its impact is equal to the case of dropping $\lfloor 1/\lambda \rfloor$ packets of sensing data. Based on this observation, we implement the buffer of each sensor by a *priority queue*. When a CH or forwarding node gets one compressed packet, it will put this packet in front of other uncompressed packets in the buffer. For the same type of packets, they are placed in a FIFO (first-in, first-out) manner. In this way, we can minimize the number of compressed packets to be dropped due to buffer overflow, thereby reducing the data loss rate in the WSN.

4.3 Grid Adjustment Procedure

As discussed earlier in Section 1, diverse sensing rates of sensors may worsen the situation of buffer overflow at CHs in cluster-based routing protocols. To conquer this problem, E-DSR dynamically changes the grid structure (by dividing or merging grids) based on the traffic loads of CHs with the help of the grid adjustment procedure. Specifically, when some sensors in a grid accelerate their sensing rates (e.g., due to the detection of events), their CH would be confronted with buffer overflow. In this case, the grid should be split into subgrids to share the load of that CH. On the other hand, when the sensors in these subgrids restore their sensing rates (e.g., due to disappearance of events), they can be merged together to improve transmission efficiency. Below, we detail the operations of grid split and mergence in this procedure.

4.3.1 Grid Split

When a CH is burdened with a heavy traffic load, there is a high possibility that the CH will start dropping some packets. Thus, we can take this phenomenon (i.e., buffer overflow) as an indicator to determine whether to adopt the grid split operation. In this way, we can reduce the overhead of the CH in terms of estimating its traffic load.

Specifically, if the number of consecutive occurrences of buffer overflow at the CH reaches a threshold ζ, the grid split operation is used to share its load with others. To do so, we divide the CH's grid into four equal subgrids (in a crisscross shape). For ease of presentation, let us call the grid to be split the *parent grid* and each subgrid a *child grid*. In each child grid, a CH is selected according to the rules mentioned in Section 4.1.

The CHs in the parent grid and each child grid are referred to as the *parent CH* and a *child CH*, respectively. Similarly, the child CH collects the sensing data from all members in its child grid and then encapsulates the collected data. In case that the parent grid is not C_{end}, the child CH forwards compressed packets to its parent CH, which will be further relayed to the sink based on the rules discussed in Section 4.2. Otherwise, the child CH directly forwards its compressed packets to the sink.

4.3.2 Grid Mergence

After collecting sensing data from sensors, each child CH reports the number of packets in its buffer (i.e., buffer length) to the parent CH. If the sum of buffer lengths of the four child CHs is below the maximum buffer size B, a notification of *potential mergence* is triggered at the parent CH. Once the number of consecutive occurrences of potential mergence goes beyond threshold ζ, it implies that the aggregate traffic load in the parent grid goes back to normal. Therefore, these four child grids can be merged together and the roles of child CHs are revoked accordingly. In this case, the sensors in the parent grid will change to forward their data to the parent CH.

4.4 Discussion

As compared with most of existing cluster-based routing protocols, our proposed E-DSR protocol has four novel designs to save more energy of sensors on relaying sensing data and thus improves their energy efficiency in terms of packet routing as follows:

First, a number of protocols usually pick the sensor closest to either the cluster's center (i.e., L_c) or the sink (i.e., L_n) to serve as the CH. In contrast with these protocols, E-DSR considers both the energy expense for members to forward their sensing data to the CH and the amount of energy required by the CH to do the routing job when choosing between L_c or L_n by using Eqs. (7) and (8). In this way, we can reduce energy consumption of all nodes (including the CH) on data transmissions in each cluster.

Second, many protocols assume that sensors have an equal sensing rate and thus prefer choosing the sensor which currently has the most energy to serve as a CH. However, they would choose the sensor with a higher sensing rate to be the CH in practice, which burdens it with a heavy load and fast drains the sensor of energy. On the contrary, E-DSR considers "expected" residual energy (ERE) of a sensor by Eq. (9), which deducts the amount of energy consumed on the sensing job in the future from its current energy. Therefore, E-DSR can overcome the problem encountered by existing protocols. Moreover, E-DSR selects CHs by referring to not only the locations but also ERE of sensors by Eq. (10), where coefficients α and β give flexibility on the CH selection.

Third, in our packet forwarding procedure, each CH h_x will not simply transmit compressed packets to the CH h_y in the next-hop grid, because h_x may consume more energy on sending data to h_y when h_y is far away from h_x. Instead, E-DSR picks a forwarding node s_j from the sensors in the next-hop grid by Eq. (12), where the amount of energy spent to send data along the path $h_x \rightarrow s_j \rightarrow h_y$ is decreased and s_j also has more ERE to help relay data. In the way, each CH need not send packets to the next-hop node far away from it, thereby further conserving energy of the CH.

Fourth, E-DSR adopts a dynamic grid structure to cope with the situation where sensors will change their sensing rates and impose their CHs with different degrees of traffic loads. In particular, when parts of sensors in a grid speed up sensing rates as they detect events, the grid is adaptively divided into child grids to share the traffic load of its CH (and avoid buffer overflow at that CH). On the other hand, child grids would be merged together when their sensors have lower sensing rates. In this way, the parent CH can improve the performance of data compression by collecting more packets of sensing data, thereby also increasing the transmission efficiency of the merged grid. In Section 5.6, we will investigate the effect of grid adjustment on E-DSR's performance.

These special designs distinguish our E-DSR protocol from existing ones, which helps prolong network lifetime and also mitigate data loss in WSNs.

5 Performance Evaluation

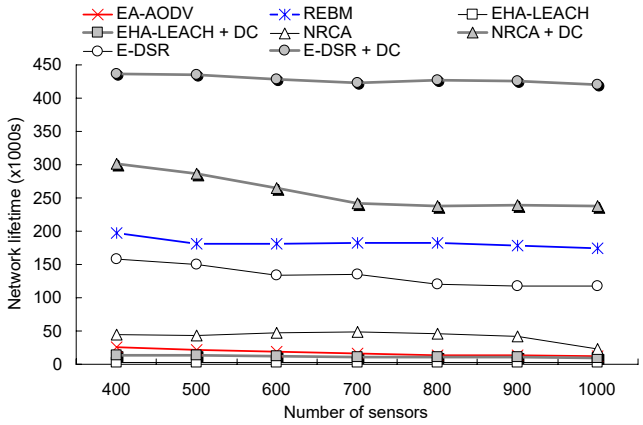
To evaluate performance of different routing protocols, we simulate a $400\,\mathrm{m} \times 400\,\mathrm{m}$ sensing field, on which 400 to 1000 sensors are deployed in a uniform distribution. The communication range r_c of sensors is 150 m, and they form a connected network. Each sensor produces a 200-byte packet of sensing data in a period depending on its sensing rate. The buffer size B is set to 200 and 400 packets. The probability for a sensor to successfully send one packet to its neighbor in the MAC layer is 0.95.

To estimate the amount of energy spent by sensors, we set the parameters in Section 3.2 as follows: 1) $V_{\mathrm{Se}} = 1.5\,\mathrm{V}$, $A_{\mathrm{Se}} = 25\,\mathrm{mA}$, and $T_{\mathrm{Se}} = 0.25\,\mathrm{ms}$ for the sensing operation, 2) $\xi_1 = 50\,\mathrm{nJ/bit}$, $\xi_2 = 100\,\mathrm{pJ/bit}$ per square meter, and $\varepsilon = 2$ for the transmission operation, and 3) $\xi_3 = 50\,\mathrm{nJ/bit}$ for the reception operation. The battery capacity (i.e., E) of each sensor is 6480 J.

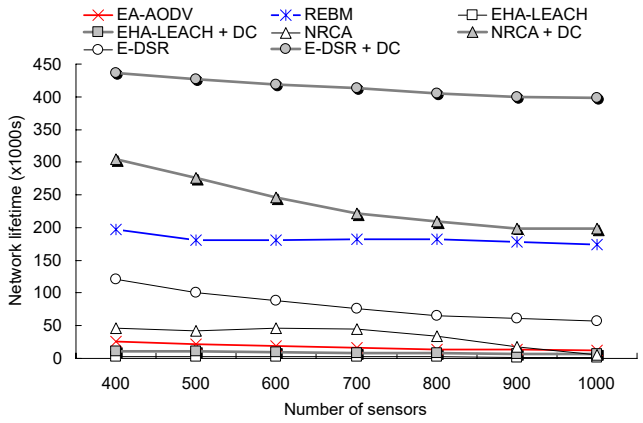
To imitate traffic flows in the WSN, we consider two scenarios for sensors to produce packets of sensing data. In the *ordinary reporting scenario*, one third of sensors have a sensing rate of 1/360 (i.e., each of them produces one packet in every 360 seconds), one third of sensors have a sensing rate of 1/480, and other sensors have a sensing rate of 1/720. Each type of sensors are randomly deployed in the sensing field. However, all sensors never change their sensing rates during network lifetime. In the *event reporting scenario*, one event occurs at an arbitrary position in the sensing field every 10800 seconds. When a sensor detects the event, its sensing rate is raised to 1/45, 1/60, 1/90 if the original rate is 1/360, 1/480, and 1/720, respectively. Each event lasts 1800 seconds. After the event disappears, sensors will restore their sensing rates. According to the discussion in Section 3.3, network lifetime is defined by the time-span since the WSN starts operating until the first sensor exhausts energy.

We compare E-DSR with two flat routing protocols, EA-AODV [20] and REBM [26], and also two cluster-based routing protocols, EHA-LEACH [37] and NRCA [43], discussed in Section 2. For cluster-based routing protocols, we consider both cases of using and not using data compression. In the case of using data compression, each CH adopts the algorithm in [48] (whose compression ratio λ is 0.25) to encapsulate its collected packets. We adopt the term "+ DC" in simulation figures to indicate the case of using data compression. As for E-DSR, we set $\alpha = 0.2$, $\beta = 0.8$, $\delta = 0.1$, and $\zeta = 2$. In Section 5.5, we will investigate their effects on E-DSR's performance.

To measure network lifetime more accurately, we also take into account the control overhead of each routing protocol. In particular, for both EA-AODV and REBM, the cost for sensors to exchange RREQs and RREPs is considered as a part of their energy consumption. For EHA-LEACH, we compute the extra energy expense of sensors to exchange control messages for the election of CHs. Since NRCA and E-DSR adopt grid structures for the clustering purpose, the overhead of grid-structure maintenance is included in the energy evaluation.

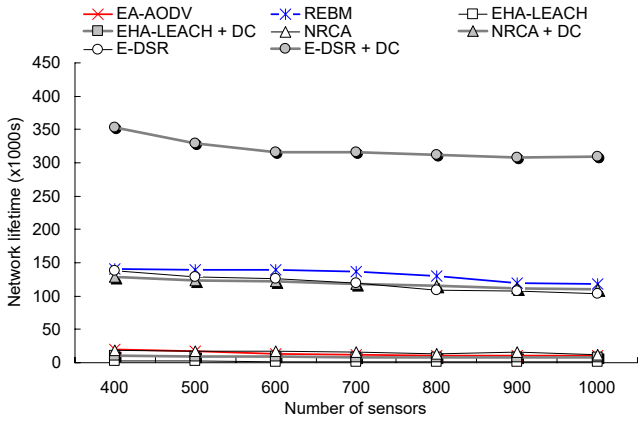


(a) $B = 200$ packets

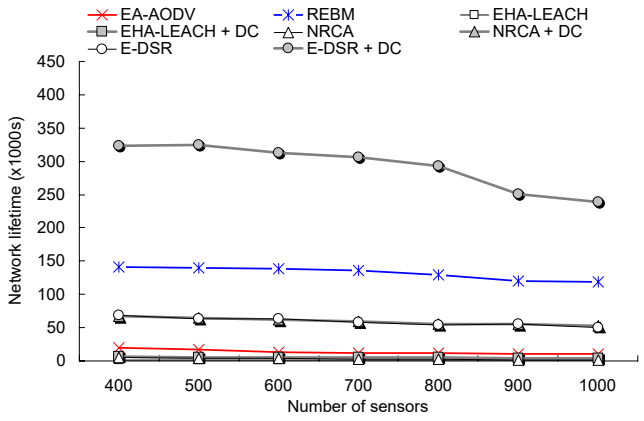


(b) $B = 400$ packets

Fig. 5: Comparison on network lifetime in the ordinary reporting scenario.



(a) $B = 200$ packets



(b) $B = 400$ packets

Fig. 6: Comparison on network lifetime in the event reporting scenario.

5.1 Comparison on Network Lifetime

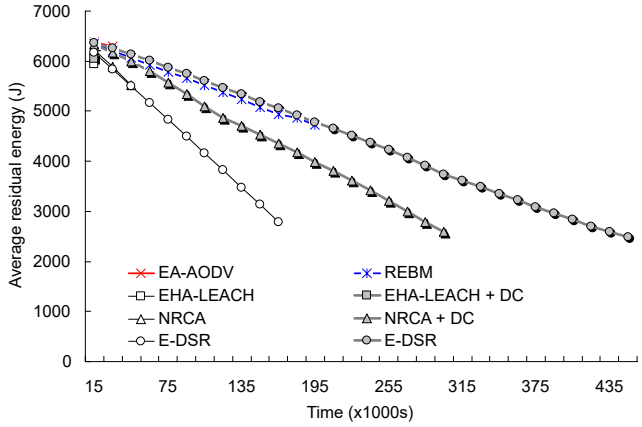
Let us first evaluate network lifetime by different routing protocols in the ordinary reporting scenario, as shown in Fig. 5. For flat protocols (i.e., EA-AODV and REBM), enlarging buffer size B has almost no impact on lifetime, because they do not use CHs for routing. In EA-AODV, sensors spend more energy on exchanging RREQs and RREPs. Moreover, it prefers selecting shorter paths. In this case, some sensors with less energy may be included in the selected paths, thereby shortening lifetime. REBM always picks sensors with more energy to be relay nodes, so it can improve lifetime than EA-AODV. However, as will be discussed later in Sections 5.3 and 5.4, REBM actually drops lots of packets (due to finding much longer routing paths). That is why REBM has longer lifetime than other methods (including EA-AODV and cluster-based protocols without data compression).

On the other hand, increasing B allows CHs keeping more packets sent from their members. In this case, CHs transmit more packets and spend more energy. Thus, cluster-based protocols (i.e., EHA-LEACH, NRCA, and E-DSR) have slightly shorter lifetime when B increases. In EHA-LEACH, the CHs in large groups need to relay data for more members. In addition, a CH far from the sink has to employ large power to transmit data. Thus, some CHs may die quickly, which much degrades lifetime in EHA-LEACH. Because NRCA selects the sensor with the most energy to be the CH in each grid, it increases potential usage time of CHs and prolongs lifetime than EHA-LEACH. As compared with NRCA, E-DSR takes account of both sensors' positions and their RER on the selection of CHs or forwarding nodes. Thus, E-DSR can avoid choosing sensors with high sensing rates to be CHs, and further save their energy. From the result in Fig. 5, both NRCA and E-DSR can substantially increase lifetime when data compression is applied. Furthermore, E-DSR (with data compression) always has the longest lifetime, which demonstrates its energy efficiency in routing.

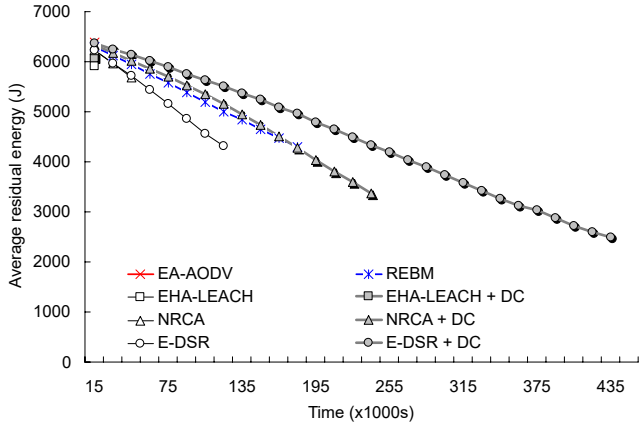
Fig. 6 gives network lifetime in the event reporting scenario, where sensors will speed up sensing rates if they detect events. Thus, each protocol has shorter lifetime as compared with the ordinary reporting scenario. Besides, since sensors produce more sensing data, more packets would be dropped by CHs due to buffer overflow when B is small. In this case, CHs forward relatively fewer packets and save their energy accordingly. That is why lifetime increases in EHA-LEACH, NRCA, and E-DSR when $B = 200$ packets. Thanks to the CH reselection by Eq. (15), E-DSR can let sensors do the routing job by turns and balance their energy consumption. Therefore, E-DSR keeps higher lifetime than most of other methods, especially when data compression is applied.

5.2 Comparison on Residual Energy

Next, we measure the average residual energy of sensors as time goes by. Fig. 7 and 8 give experimental results in the ordinary and event reporting scenarios, respectively, where B is set to 200 packets. EA-AODV lets sensors save the most energy, but its lifetime is pretty short. This phenomenon shows that EA-AODV causes unbalanced energy consumption of sensors, where those sensors close to the sink will run out of

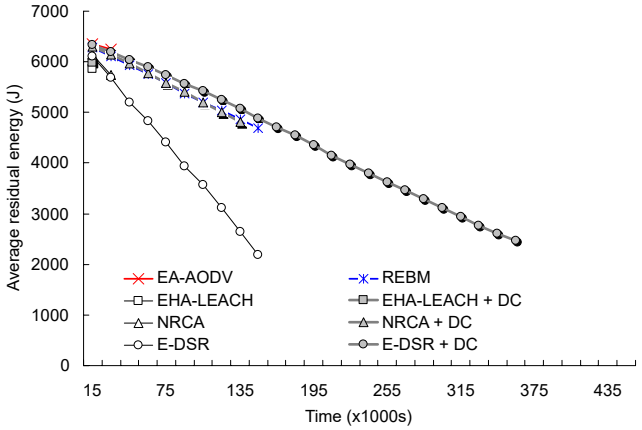


(a) 400 sensors

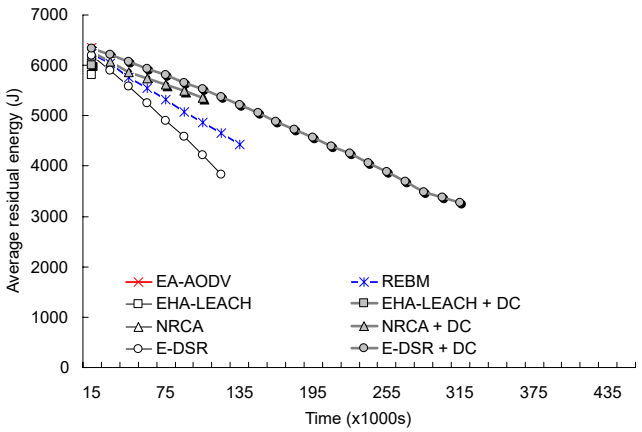


(b) 800 sensors

Fig. 7: Comparison on the average residual energy of sensors in the ordinary reporting scenario.



(a) 400 sensors



(b) 800 sensors

Fig. 8: Comparison on the average residual energy of sensors in the event reporting scenario.

energy quickly (i.e. the energy hole problem). On the contrary, EHA-LEACH makes sensors spend the most energy, because some CHs have to transmit packets to the sink far away from them. In this case, it results in shorter lifetime. By dropping many packets, REBM conserves more energy of sensors and extends lifetime accordingly.

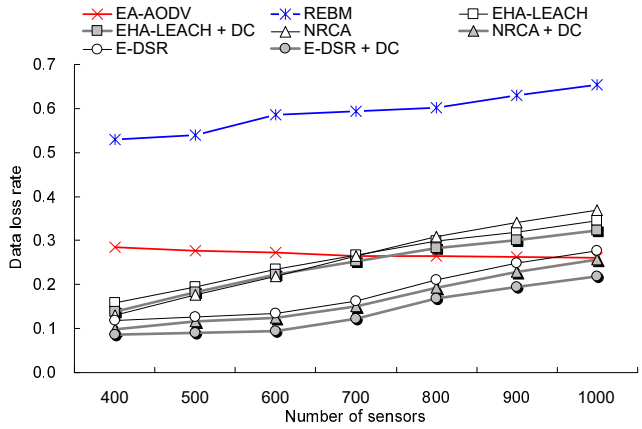
Without data compression, NRCA and E-DSR result in similar residual energy of sensors, because both of them adopt a grid structure to route packets. However, E-DSR significantly extends lifetime than NRCA in each scenario, which verifies that E-DSR achieves high energy utilization of sensors as compared with NRCA. By using data compression, E-DSR can better utilize the energy of sensors on data transmissions and further balance their energy consumption, especially in the ordinary reporting scenario.

5.3 Comparison on Data Loss

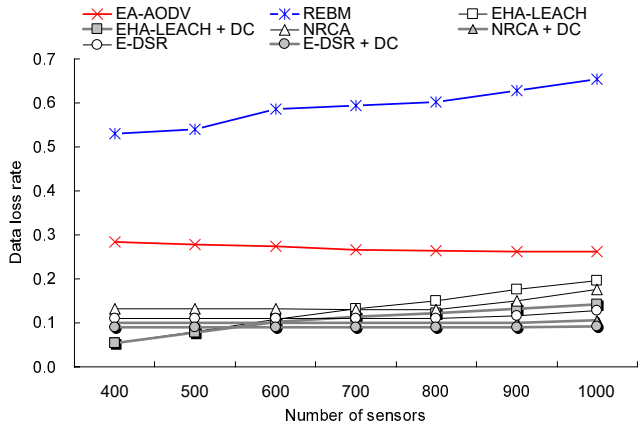
After that, let us investigate the amount of lost data by each routing protocol. Fig. 9 gives the data loss rate in the ordinary reporting scenario. As discussed earlier in Section 3.3, data loss could be caused by transmission failure or buffer overflow. Since neither EA-AODV nor REBM cluster sensors, their data loss rates would be decided solely by transmission failure. In our simulations, the probability of transmission failure in the MAC layer is a constant (i.e., 0.05), so changing buffer size B has almost no effect on the data loss rate in flat routing protocols. For EA-AODV, routing paths with fewer hop counts will be chosen, so it can reduce the data loss rate. On the contrary, REBM prefers selecting a neighbor close to the sender to be a relay node. Thus, it may construct routing paths with many hop counts, especially when there are more sensors. In this case, REBM would suffer from serious transmission failure, thereby resulting in the highest data loss rate.

On the other hand, the data loss rates of cluster-based routing protocols substantially decrease when B increases, since each CH has more buffer space to cache the sensing data sent from its members. Besides, using data compression helps decrease the data loss rate. In particular, all cluster-based routing protocols have lower data loss rates than flat ones in the case of B = 400 packets. By adopting a dynamic grid structure, our E-DSR protocol can adaptively split a grid with more traffic demands to share the load of its CH. Thus, E-DSR has a much lower data loss rate than other protocols.

Fig. 10 then compares the data loss rate in the event reporting scenario. Because parts of sensors accelerate their sensing rates due to detecting events, each protocol will have a higher data loss rate. Such a phenomenon is more significant in cluster-based routing protocols, as the traffic flows in each grid will converge on its CH. Similarly, E-DSR keeps the lowest data loss rate in most cases, since it can divide a grid when the CH suffers from buffer overflow. This result shows the flexibility of grid adjustment in E-DSR for reducing lost data caused by buffer overflow at CHs.

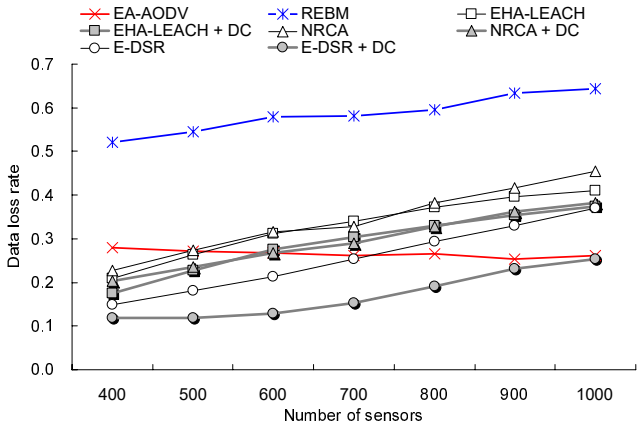


(a) $B = 200$ packets

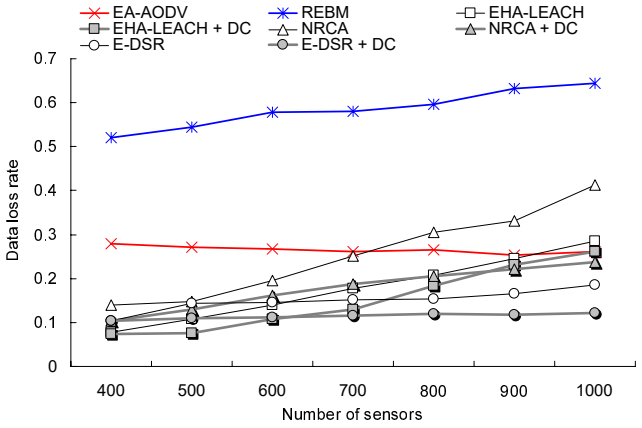


(b) $B = 400$ packets

Fig. 9: Comparison on the data loss rate in the ordinary reporting scenario.



(a) $B = 200$ packets



(b) $B = 400$ packets

Fig. 10: Comparison on the data loss rate in the event reporting scenario.

5.4 Comparison on Path Length

In wireless ad hoc networks, because the destinations of nodes are different, cluster-based routing protocols may construct longer routing paths than flat ones. However, in a WSN, the sink is usually the common destination of every sensor. Therefore, CHs can first build a stable path to reach the sink, and each of other sensors then directly forwards packets to its CH, which will be routed through that path. In this case, cluster-based routing protocols would be likely to find shorter routing paths as compared with flat ones.

To verify the aforementioned argument, we compare the average hop count of routing paths found by each protocol, as shown in Fig. 11. Since changing the buffer size or adopting data compression will not affect the way that each protocol constructs its routing paths, we set B to 200 packets and data compression is not applied in the experiment. Besides, only the E-DSR protocol will dynamically change routes due to event occurrence, so we show the result of E-DSR in both ordinary and event reporting scenarios. For other protocols, we just show their results in the ordinary reporting scenario (as the data will be the same with the event reporting scenario).

From Fig. 11, REBM always constructs much longer routing paths than others, even though it is a flat routing protocol. The reason is that REBM selects a relay node for each sensor based on the three rules: 1) the node with the maximum energy, 2) the node closest to the sender, and 3) the node that has the fewest children. When there are more sensors in the WSN, the routing paths found by REBM will thus become longer. Another flat routing protocol, namely EA-AODV, seeks to find routing paths with fewer hop counts and whose sensors possess more energy. Thus, it can significantly reduce the path length as compared with REBM.

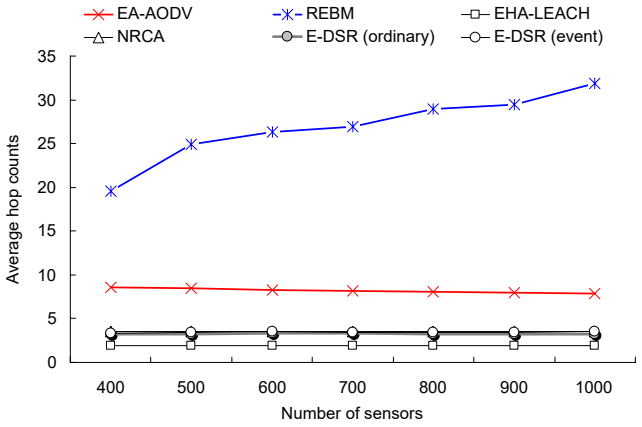
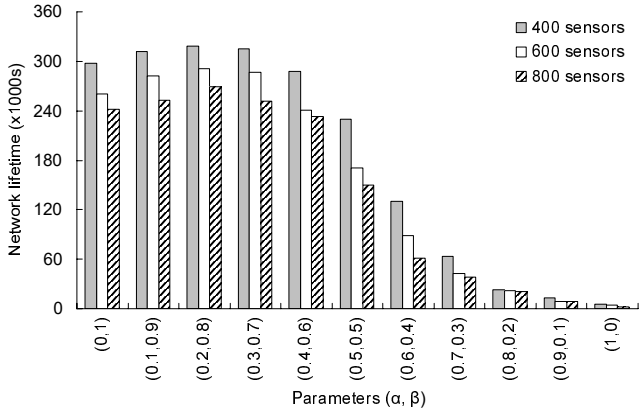
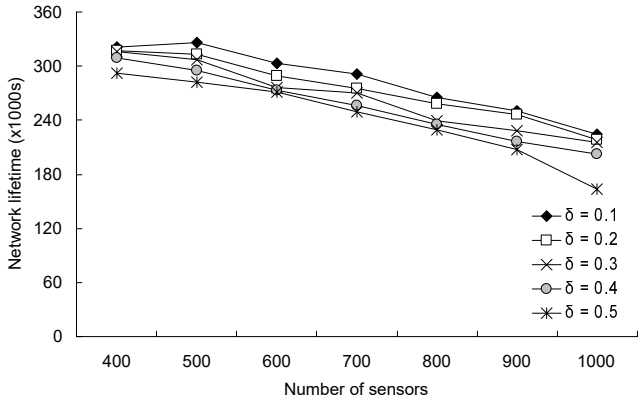


Fig. 11: Comparison on average hop counts of routing paths found by different protocols.

Each cluster-based routing protocol evidently finds much shorter routing paths than both REBM and EA-AODV in Fig. 11. For EHA-LEACH, because each CH can directly transmit packets to the sink, it thus results in the smallest average hop count. Due to employing grid structures, E-DSR and NRCA have similar average hop counts. For our E-DSR protocol, the grid adjustment procedure slightly increases the length of a routing path, as only those grids with heavy traffic loads will be split. Based on the experimental result, we show

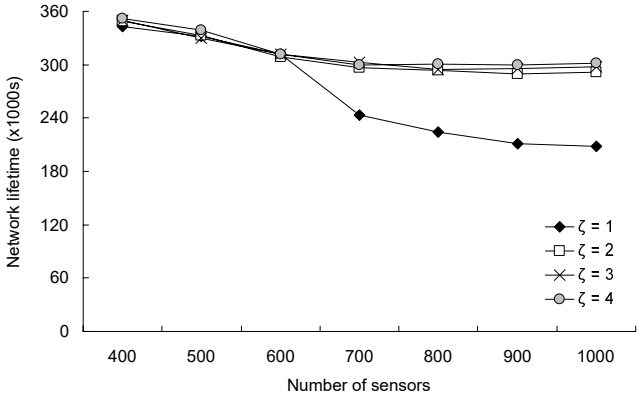


(a) Parameters α and β

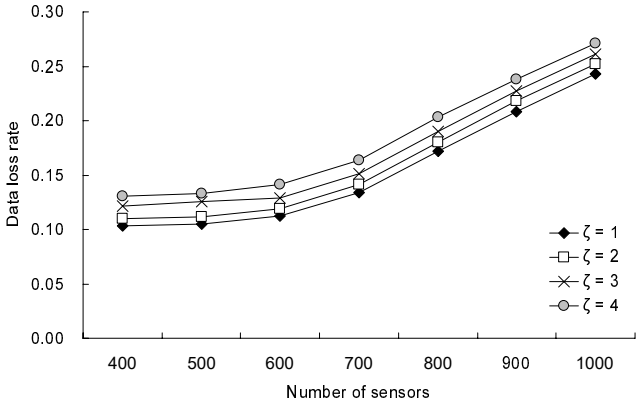


(b) Parameter δ

Fig. 12: Effect of parameters α, β, and δ in E-DSR on network lifetime.



(a) Network lifetime



(b) Data loss rate

Fig. 13: Effect of parameter ζ on E-DSR's performance.

that cluster-based routing protocols can actually construct shorter routing paths than flat ones in WSNs.

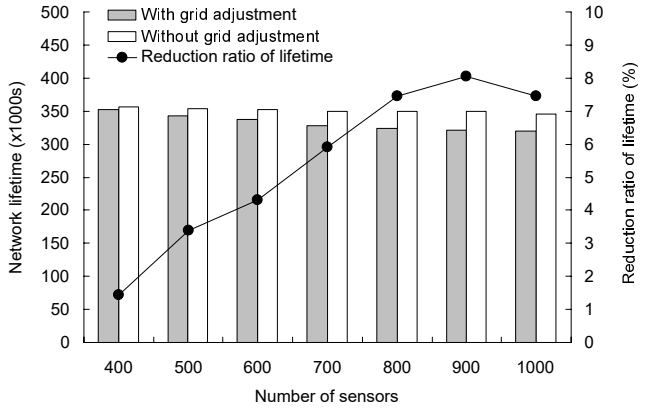
5.5 Effect of Parameters

There are four parameters used in the E-DSR protocol to control its behavior. In this section, we look into their effect on the performance of E-DSR, including network lifetime and the data loss rate. Here, our discussion aims at the ordinary reporting scenario and the case of using data compression, since the effect of different scenarios and data compression has been assessed in Sections 5.1 and 5.3.

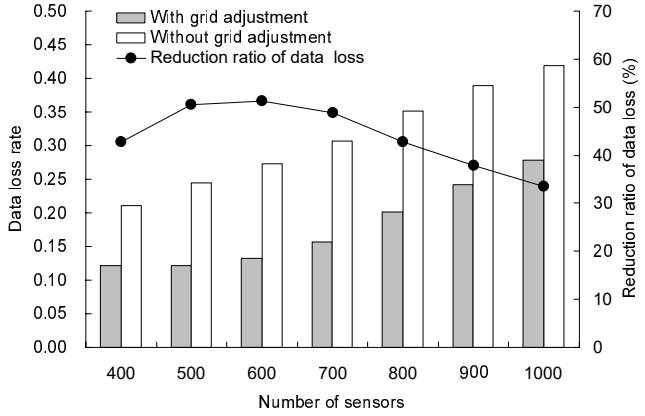
In Eqs. (10) and (12), parameters α and β co-decide the weight of each sensor for the selection of CHs and forwarding nodes, respectively. Fig. 12(a) analyzes their effect on network lifetime when there are 400, 600, and 800 sensors. In this experiment, the buffer size (i.e., B) is set to 400 packets. Since $\alpha + \beta = 1$, increasing α will decrease β, and vice versa. Evidently, when β is below 0.7, network lifetime decreases drastically as α increases. The reason is that α and β determine the proportions of a sensor's position (i.e., $\tilde{D}_i$) and its ERE E_i^R on the calculation of its weight, respectively. When β becomes small, there is a good possibility that some sensors are frequently chosen as CHs (because they are close to L_c or L_n) or forwarding nodes, thereby consuming their energy more quickly. On the other hand, when β is larger than 0.7, increasing α slightly extends network lifetime. The reason is that sensors may have similar ERE if they are close in sensing rate. In this case, the sensor closer to the desired position (e.g., L_c or L_n) could spend less energy on transmitting packets and thus extend its lifespan. Based on the result in Fig. 12(a), we suggest setting $\alpha = 0.2$ and $\beta = 0.8$ in order to maximize network lifetime.

In Eq. (15), the parameter δ is used to check whether to reselect the CH in a grid. Specifically, if the reselecting indicator $\hat{I}_k$ is above δ, the CH selection procedure is invoked to pick a new CH for the grid. Fig. 12(b) presents the effect of δ on network lifetime, where B is set to 400 packets. Recall in the calculation of $\hat{I}_k$ by Eq. (14), the condition of $\hat{I}_k \geq \delta$ implies that the CH's residual energy falls below a $(1 - \delta)$ ratio of the average energy of sensors in the grid. Thus, a larger δ value means that the selected sensor has to act as the role of CH for a longer time. In this case, the sensor will spend more energy on the routing job, which shortens its lifespan. According to the result in Fig. 12(b), we suggest setting δ to 0.1 (or a smaller value) to prolong network lifetime.

In Section 4.3, we use parameter ζ to decide whether to divide or combine grids. In particular, only if the CH successively encounters buffer overflow for ζ times, will its grid be split. On the other hand, when the number of consecutive occurrences of potential mergence reaches ζ, the four child grids will be merged together. Fig. 13 shows the effect of ζ on both network lifetime and the data loss rate, where B is set to 200 packets (because a smaller buffer size makes buffer overflow become easier). In Fig. 13(a), network lifetime decreases substantially when there are more than 600 sensors by setting $\zeta = 1$. The reason is that it is pretty easy to trigger the grid adjustment procedure, so grid split or mergence becomes more frequently. In this case, sensors spend more energy on exchanging control messages for the procedure, thereby shortening network lifetime. On the other hand, increasing ζ also increases the data loss rate in Fig. 13(b), because some CHs



(a) Network lifetime



(b) Data loss rate

Fig. 14: Effect of the grid adjustment procedure on E-DSR's performance.

may have heavier traffic loads but grid split is not conducted due to the constraint of ζ. From the results in Fig. 13, we suggest setting $\zeta = 2$ to achieve longer network lifetime while keeping a lower data loss rate.

5.6 Effect of Grid Adjustment

Lastly, we evaluate how the grid adjustment procedure affects E-DSR's performance in terms of both network lifetime and the data loss rate. By setting the buffer size to 200 packets, Fig. 14 gives experimental results with and without the grid adjustment procedure, where we employ the ordinary reporting scenario and the case of using data compression.

As discussed in Section 5.5, grid split and mergence involves in exchanging control messages among sensors. Therefore, network lifetime in Fig. 14(a) slightly reduces if the grid adjustment procedure is adopted, especially when the network scale becomes large. On the average, the grid adjustment procedure shortens around 5.4% of network lifetime in E-DSR. On the other hand, since the traffic loads of busy CHs can be shared out through splitting their grids, the data loss rate in Fig. 14(b) declines significantly with grid adjustment. Specifically, this procedure decreases 43.9% of lost packets on the average. The above results show that the grid adjustment procedure plays a conspicuous part in E-DSR, since it helps substantially reduce lost packets caused by buffer overflow without greatly shortening network lifetime.

6 Conclusion and Future Work

Many sensors are powered by small and non-rechargeable batteries, so it is critical to conserve energy of sensors. Consequently, an efficient cluster-based routing protocol, namely E-DSR, is developed in this paper to decrease energy consumption of sensors on reporting their sensing data to the sink. Unlike most of existing protocols, E-DSR takes account of diverse sensing rates of sensors due to detection of events or application requirements. It divides a WSN into grids and selects one CH in each grid such that energy consumption of all nodes in the grid can be reduced and the CH has more ERE on conducting the routing mission. Moreover, E-DSR adaptively changes the grid structure and routing paths based on the traffic loads of CHs, so as to eliminate buffer overflow at CHs and improve transmission efficiency. Simulation results verify that our proposed E-DSR protocol substantially extends network lifetime and also keeps a lower data loss rate, as compared with EA-AODV, REBM, EHA-LEACH, and NRCA protocols. Moreover, we evaluate the effect of parameters and also the grid adjustment procedure on the performance of E-DSR.

Since the sleep mechanism is popularly used in WSNs to help improve energy efficiency of sensors, it deserves further investigation on how to efficiently integrate the E-DSR protocol with the sleep mechanism in the future work. In particular, we should ameliorate the selection policy of both CHs and forwarding nodes by taking the sleeping periods and frequencies of sensors into account. Furthermore, a buffering mechanism has to be carefully designed to deal with the case where some data will be sent to those sensors going to sleep.

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