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Energy-Efficient Cooperative Routing Scheme for Heterogeneous Wireless Sensor Networks

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ABSTRACT Generally, routing techniques are essential for Wireless Sensor Networks (WSNs) to deliver data packets to their destinations (also known as sinks). For a practical application, sensors are deployed to monitor environmental changes and events. Most WSNs detect specific events in their specific environments. But, different WSNs may monitor different events with different sensors in the same area. For example, a smart-home WSN deploys thermal sensors/meters to measure indoor and outdoor temperatures, body-temperature sensors to detect thief intrusion, etc. Also, in the underlying house, there is a health WSN which utilizes physiological sensors to monitor patients' health condition. In other words, several WSNs of different purposes co-exist in the same geographical area. Currently, each WSN's data delivery is independent from others'. Basically, if all sensors in such a multi-WSNs environment can share their routing paths/nodes and relay event packets for other WSNs, the delivery efficiency can be enhanced since many more sensors can be found there for packet relay. Consequently, the transmission energy can be reduced since energy consumed for wireless transmission is proportional to d^2 where d is the transmission distance between sender and receiver. Therefore, in this study, we propose an energy saving routing mechanism, named Energy-Efficient Cooperative Routing Scheme for Heterogeneous Wireless Sensor Networks (EERH for short), in which several WSNs deployed in the same geographical environment form a heterogeneous sensor network and sensors relay packets for its own WSN and also for other WSNs. Routing paths are dynamically established according to the transmission directions of event packets and the residual energy of the underlying sensors and their neighbors. In addition, the packets routed to the same direction by the same sensors are aggregated to save delivering energy. Moreover, the network parameters of the EERH, like propagation delay of an event packet and the transmission distance of a sensor, are adjustable so as to satisfy the practical environment needs. Simulation results show that the EERH efficiently extends the lifetime of a heterogeneous WSN.

INDEX TERMS Wireless sensor networks, heterogeneous wireless sensor networks, energy efficient, cooperative routing.

I. INTRODUCTION

In recent years, Wireless sensor networks (WSNs) have been popularly applied to monitor our environmental changes and events. When a sensor detects the occurrence of an event, it produces event packets and delivers it to notify the corresponding sinks, from which system administrators can realize the real situation of the monitoring environment and then react properly. However, sensors are often deployed to detect specific events [1]. In other words, different WSNs utilize different sensors to detect different events. But sometimes, several WSNs co-exist in a geographical area [2], [3]. For example, a smart-building WSN [4] prepares sensors to detect human movement or body temperature for turning on/off corridor lights. Another WSN is deployed in this building to detect indoor temperature for controlling air conditioners. Further, if this building is a hospital, many sensors are utilized to monitor patients' physiological conditions [5]. In fact, these co-location WSNs together form a heterogeneous WSN.

Currently, routing paths of different WSNs are mutually independent, meaning that different WSNs route their

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own packets through their own routing paths and sensors. On receiving a packet belonging to other WSN, a sensor drops this packet without relaying it to the corresponding sink. In fact, if sensors can forward receiving packets for other WSNs, basically, the routing efficiency will improve since many more sensors can relay packets in this heterogeneous WSN, thus shortening the distance between two neighbor sensors and then increasing the sensor density of this monitoring environment. The shorter the distance d, the lower the consumed packet-transmission energy E where $E = f(d^2)$.

On the other hand, if a sensor forwards all the packets it receives toward their sinks, due to wireless broadcast, lots of redundant packets of the same one will flow in the network. We call this phenomenon packet storm or broadcast storm which wastes a great amount of energy for unnecessary redundant transmissions. Further, if no sensors inform sinks of an occurred event in time, the problem solving efficiency of the monitoring system is then poor. Generally, this efficiency is an important factor when evaluating the performance of a monitoring WSN [6].

Moreover, energy support is one of the key concerns of WSNs. Usually, sensors are small in size. If their energy is provided by batteries, the amount is often limited. We may design energy-efficient mechanisms for sensors, or design specific hardware to harvest energy from other equipment or from environment. Of course, designing such hardware takes time.

Therefore, in this study, we propose an energy saving routing mechanism, named Energy-Efficient Cooperative Routing Mechanism for Heterogeneous Wireless Sensor Networks (EERH for short), in which WSNs deployed in the same geographical environment form a heterogeneous sensor network and sensors relay packets generated by its own WSN and other WSNs. The routes for packet delivery are determined dynamically according to the transmitted directions of events as well as the residual energy of underlying sensors and their neighbors. Also, those packets routed to the same direction by the same sensor are aggregated as one to save delivering energy and efficiently notify the corresponding sinks. Simulation results show that the EERH efficiently extends the lifetime of a heterogeneous WSN. Thus, the monitoring system can live longer and the sinks are able to receive many more event packets. Our previous research results are published in [7]. In the following, we use path and route interchangeably, even though someone defines them differently.

The rest of the paper is organized as follows. Section 2 describes background and related studies of this paper. Section 3 introduces the EERH in detail. Simulation results are evaluated and discussed in Section 4. Section 5 concludes the paper and outlines our future studies.

II. RELATED STUDIES

Lots of researchers pay attention to energy efficiency of sensors because their energy is often limited due to powered by battery. To reduce energy consumption, Agarkhed *et al.* [8], [9] classified events and assigned priorities to them. Event packets are sent following their priorities. A lower-priority packet may wait and aggregate with later packets of higher priorities. In other words, event notification efficiency and energy consumed for packet delivery are their main focuses.

For heterogeneous wireless sensor networks, Mohammed and Elrahim [10], Liu *et al.* [11], and Singh *et al.* [12] proposed cluster-based routing protocols for balancing energy consumption among sensors. Sensors of a cluster elect their head to cooperate packet collection and delivery. Nevertheless, such an election consumes lots of energy and a packet may pass through many more hops before arriving at the sink. The heterogeneous WSNs in these studies show that sensors with different capabilities are due to carrying different amount of energy. On the other hand, a heterogeneous WSN consists of several mutually independent WSNs, each of which has its own responsibility. Thus, the sensors and sinks deployed by different WSNs are unrelated. In fact, the heterogeneity in these studies represents that sensors with different responsibilities sense different types of events.

Alromih and Kurdi [13] chose an optimal node by collecting statuses of its neighbor sensors for packet delivery so as to reduce relaying costs. However, sensor statuses need to be collected periodically from the entire monitoring environment and the newest information requires to be maintained. Both consume some amount of energy.

Cheng *et al.* [14] presented that end-to-end energy costs and network lifetime cooperative routing are greatly restricted if the cooperative transmission model is not well designed. So they explore a two-stage cooperative routing scheme to improve routing energy efficiency and prolong the network lifetime by designing a core helper to determine the helper set for cooperation, formulating the two-stage link cost and selecting the optimal helper set to optimize the link cost. They also proposed a distributed two-stage cooperative routing (TSCR) scheme to minimize the end-to-end cooperative routing costs.

Dung and An [15] introduced a stability-aware cooperative routing scheme in multi-rate mobile ad-hoc wireless networks to provide high data transmission via stable and reliable routes. Their main features and contributions include using a cross-layer scheme which contains network layer, MAC layer, and physical layer, selecting a stable routing path as the main routing path, choosing relay and appropriate data rate based on RSSI, PHY delay and MAC delay and deriving mathematical models for investigating the tradeoff between point-to-point transmission rates and the corresponding effective transmission ranges. However, their focuses are not energy efficiency and lifetime of a heterogeneous WSN.

Jamalipour and Ma in the book [16] introduced that designing a cooperative routing algorithm can lead to energy savings. A minimum power cooperative routing method, which is a distributed cooperative routing algorithm, has been proposed to choose minimum-power routes. This method also guarantees network QoS. Authors further mentioned that by jointly exploring the problem of contention avoidance among multiple links in MAC layer and routing path selection in a network layer, a distributed cooperative routing scheme based on the concept of virtual node and virtual link can achieve the total transmission power savings for multi-source multi-destination multi-hop wireless networks. However, their description is on route selection, rather than relaying packets in a heterogeneous WSN.

Bosch *et al.* [17] presented that basically, management and control in wireless communication are almost mutually independent from each other, leading to poor resource usage, performance and service guarantees. They also claimed that orchestration among technologies can solve these problems and then further presented the general challenges on the management of heterogeneous wireless networks, overviewed state of the art commercial and scientific solutions and showed their strengths and weaknesses. Authors also discussed current status and future challenges that are still waiting for providing full seamless heterogeneous wireless network management.

Khalifa *et al.* [18] integrated two heterogeneous wireless technologies (such as WiFi and cellular 3G/4G) to provide reliable and fast communication among the primary and secondary distribution base stations. This integration enables the transmission of data packets of different types over two radio interfaces, making these interfaces play the role of a data pipe and observe the applicability and effectiveness of employing heterogeneous wireless networks (HWNs) so as to achieve the desired reliability and timeliness requirements of future smart grids. Their findings reveal that HWNs can be a viable data transfer option for smart grids.

To establish an energy-efficient routing path, Liu *et al.* [11], [19] considered the residual energy of sensors and the distance between sensors and sinks to prolong the lifetime of their WSN. Moreover, to help sensors to know the statuses of their neighbors, in the routing system proposed by Singh and Al-Turjman [20], a sensor attaches its current statuses to the packets sent to neighbors when it would like to communicate with its surrounding nodes. Sharma *et al.* [21], [22] shared a node's working history with its neighbors. Thus, a node can realize the statuses of its nearby sensors.

To lower energy consumption for transmissions, Israr and Awan [25] introduced the influence of data aggregation on energy consumption. The purpose is also reducing data transmission energy.

Our study aims at efficiently routing event packets to their sinks. In our monitoring environment, a sensor belonging to WSN A is able to relay packets generated by sensors of WSN B, meaning that neighbor sensors cooperate with each other to transmit packets even though they are responsible for sensing different events for different WSNs, e.g., a sensor utilized to detect body temperature for turning on/off corrido lights is able to relay packets carrying a patient's blood pressures, implying that these WSNs' network transmission protocols need to be the same, like TCP or UDP. Before transmitting a packet, residual energy of neighbor sensors and their statuses are addressed, attempting to transmit the packet to the best neighbor so as to improve energy efficiency for data transmission. Moreover, we aggregate packets and choose the relay sensors near the sink so that energy consumed for delivering an event packet will be less. In the following, event packets and packets are used interchangeably.

III. THE ARCHITECTURE OF THE EERH

We first describe the network settings/environment of the EERH, and then present the operation timings of this system. At last, the cooperation among WSNs is introduced.

A. NETWORK SETTINGS/ENVIRONMENT

Assuming that in a monitoring environment, there are n sinks, $K = \{k_i|i = 1, \ldots, n\}$, for event collection, and m sensors, $S = \{s_j|j = 1, \ldots, m\}$, for event detection and data transmission. Each sensor knows its residual energy as well as the locations of itself and all sinks. Also, there are p types of events, $E = \{e_h|h = 1, \ldots, p\}$. In general, $m \gg n, p$. Let $kr_{i,h}$ and $sr_{j,h}$ be the parameters of sink k_i and sensor s_j on events of type e_h, respectively. If sink k_i is able to collect events of type e_1, e_2, and e_3, we call that k_i is responsible for events of type e_1, e_2, and e_3 and then $kr_{i,1} = kr_{i,2} = kr_{i,3} = 1$. That is, event packets of type e_h may send to sink k_i, $h = 1, 2, 3$. If $kr_{i,h} = 0$, event packets of type e_h would not send to k_i. When sensor s_j has the ability to detect an event of type e_h, we call that s_j is responsible for event of type e_h and thus $sr_{j,h} = 1$. When $sr_{j,h} = 0$, s_j is irresponsible for detecting events of type e_h. In this study, as shown in (1).

$$\sum\nolimits_{h=1}^{p} kr_{i,h} \geq 1, \quad \forall k_i \in K,\ \forall e_h \in E \tag{1}$$

indicates that k_i can receive at least one type of event packet. As listed in (2),

$$\sum\nolimits_{h=1}^{p} sr_{j,h} = 1, \quad \forall s_j \in S,\ \forall e_h \in E \tag{2}$$

means that s_j can detect only one type of event. Moreover, each type of event has at least one sink as shown in (3).

$$\cup \left\{ e_h \left| kr_{i,h} \geq 1, \quad \forall \left(k_i, e_h\right) \in (K, E) \right. \right\} = E \tag{3}$$

In this monitoring environment, when a sensor detects the occurrence of an event, a packet of this event type will be generated and then sent to the nearest sink of this event. But if the route between the sensor and the nearest sink is unconnected or indirect [23], e.g., owing to the fact that some sensors along the nearest path have exhausted their energy, the destination sink may be one a little farther away.

The energy consumed by a sensor network includes detecting events, receiving packets, aggregating packets and transmitting packets to sinks. Among these activities, the energy consumed for transmitting event packets are much greater than that consumed by the other three sensor activities [24]. The reason is that transmission amplifiers consume more energy. Our main objective is to prolong the monitoring lifetime of a heterogeneous WSN by reducing the energy consumption for packet transmissions.

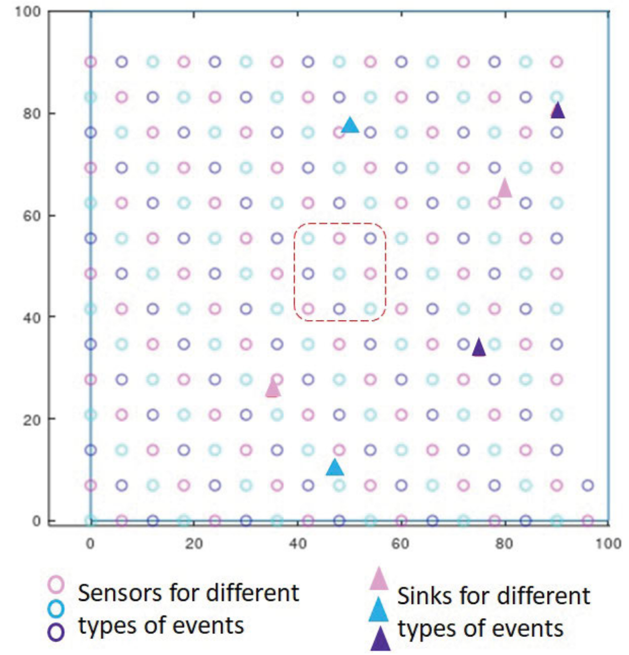

FIGURE 1. An example of our network environment. Different colors of sensors and sinks are responsible for different types of events.

Fig. 1 shows an example of our network environment, in which sinks and sensors of the same color (different colors) are responsible for the same type (different types) of events, i.e., they belong to the same WSN (different WSNs).

B. DETECTION AND LISTENING PERIODS

In the EERH, as shown in Fig. 2, the time line of a sensor is logically divided into rounds, also called time slots. A round consists of a detection period and a listening period. In the former, sensors detect events, while in the latter, sensors listen to its neighbors for receiving packets that will be relayed to sinks. The lengths of different rounds are the same. The detection periods (listening periods) in different rounds are of the same length.

Fig. 3 shows an example of hot region and sub-hot region for event detection and announcement. When the sensing range of a sensor is r, the transmission range should be longer than $2r$. Thus, we name the yellow region and gray region as hot region and sub-hot region of event E_0, respectively. In the hot region of E_0, the surrounding sensors can detect the occurrence of E_0. In addition, the sensors in the same hot region can receive the packets transmitted by others because the distance between each pair of sensors is less than $2r$. On the contrary, a packet sent by a sensor in the sub-hot region of E_0 may not directly receive by the sensors in this hot region, and vice versa. In this work, when an event e occurs, if s_j is in event e's hot region, s_j will find e and announce it. Because the sensors in e's hot region can hear the announcement issued by other sensors, this can avoid transmitting duplicate event packet of the same event.

In Fig. 4, the angle θ_1 between the two arrows $\overrightarrow{S_1S_2}$ and $\overrightarrow{S_2Sink_2}$ is larger than 90° and the angle θ_2 between the two

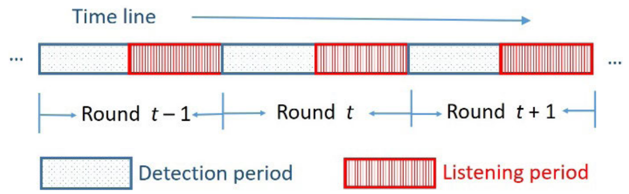

FIGURE 2. The time line of a sensor is logically divided into rounds of the same length and a round comprises a detection period and a listening period.

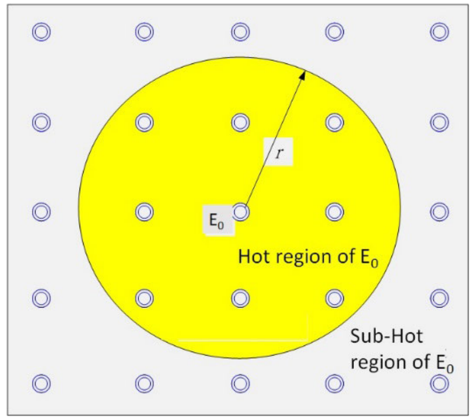

FIGURE 3. Hot region for event detection and announcement.

arrows $\overrightarrow{S_0S_3}$ and $\overrightarrow{S_3Sink_2}$ is smaller than 90°. Assuming that S_2 has received a packet P_0 which will relay to $Sink_2$, S_1 has detected the occurrence of $Event_1$ and then sends packet P_1 toward $Sink_1$ through S_2. Since the angle θ_1 is larger than or equal to 90°, we consider that P_0 and P_1 are sent to different directions. On the contrary, if S_3 has received a packet P_3 which will relay to $Sink_2$ and now it receives packet P_2 from S_0 due to discovering $Evnet_2$, since P_2 is sent toward $Sink_3$ (not shown) via S_3 and the angle θ_2 is smaller than 90°, we consider that P_2 and P_3 are transmitted to the same directions. It means that 90° is the threshold. Because when the angle is smaller than 90° and S_3 aggregates P_2 and P_3 together as one and forwards them, P_2 will also come close to $Sink_3$.

Following the hot region illustrated in Fig. 3, we show the hot region for an event packet transmission in Fig. 4 as an example. The region surrounded by orange dashed lines is the hot region for transmitting event packet P_2 owing to discovering the occurrence of $Event_2$ to $Sink_2$ because all sensors in this region can receive P_2 for the announcement of $Event_2$. When the sensors in sub-hot region relay P_2, $Event_2$ may have more than one transmission paths because some sensors may individually transmit P_2 due to unknowing the real transmission situation. If we want to eliminate the duplication of P_2 in this sub-hot region, the transmission power of a sensor should be strengthened to inform farther sensors. Hence, the energy consumption for transmitting P_2 and other event packets will be higher.

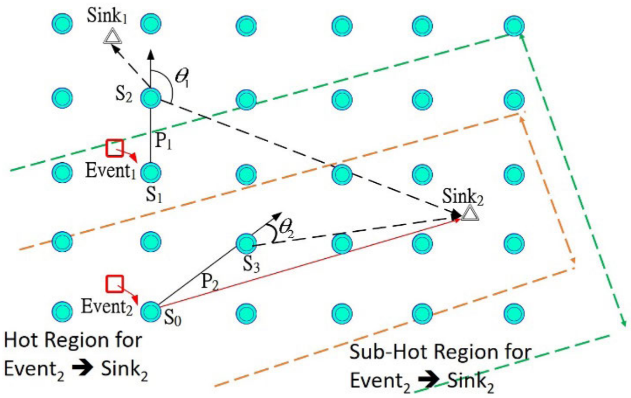

FIGURE 4. Hot region and sub-hot region for transmitting event packet P_2. The angle θ_1 between the two arrows $\overrightarrow{S_1S_2}$ and $\overrightarrow{S_2Sink_2}$ is larger than 90° and the angle θ_2 between the two arrows $\overrightarrow{S_0S_3}$ and $\overrightarrow{S_3Sink_2}$ is smaller than 90°.

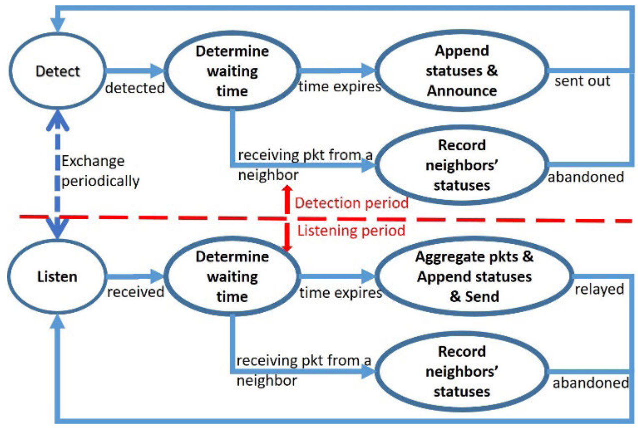

FIGURE 5. The state diagram of a sensor.

The packet forwarding procedure of the EERH is that when a sensor receives n packets, Pkt(t) $=\{p_i|i = 1, 2, \ldots n\}$, in round t, if h packets, P(t) $=\{p'_j|j = 1, 2, \ldots .h\}$, $1 \leq h \leq n$, are transmitted to the same direction, the h packets are then aggregated into one and forwarded. Let CD_j^t, CT_j^t, CR_j^t, and CA_j^t be the energy consumed, respectively, for event detection, data transmission, packet receiving, and packet aggregation, by s_j during time slot t. Let E_j^t be the residual energy of sensor s_j in time slot t as

$$E_j^t = E_j^{t-1} - CD_j^t - CT_j^t - CR_j^t - CA_j^t,$$
$$E^{full} \geq E_j^t \geq 0 \& s_j \in S \tag{4}$$

where $t = 1, 2, \ldots, E_j^0 = E^{full}$ is the full energy of a sensor when $t = 1$. If the energy possessed by a sensor is 0, this sensor can no longer monitor the environment. Moreover, all sensor networks aim to inform sinks of the occurrence of events. When more than ratio p events are uninformed, we consider that the lifetime of the sensor network ends. We would like to maximize the lifetime of environmental monitoring, e.g., T, subject to that the number of uninformed events is less than ratio p as (5).

$$\text{Objective : Maximize } T \text{ defined as the number of uninformed events which is less than the ratio } p \text{ when } u \times t \leq T \tag{5}$$

where t and u are the number of rounds and time duration of each round, respectively.

C. COOPERATION AMONG NETWORKS

In the EERH, three items are taken into account, including the energy balance among sensors, sensor parameters on QoS and propagation delays of event packets. To achieve this, a sensor maintains statuses of neighbors in its relaying list with which to determine when to announce a detected event (i.e., transmitting an event packet P), or when to send a receiving/relay packet P, e.g., at time t which is called delivery time point (DTP) of P, no matter whether P is an announcement packet or a relayed packet. The waiting time (WT) before transmitting P is defined as

WT = DTP − current system time.

To avoid transmitting duplicate packets, the underlying sensor in the WT keeps listening to its neighbors for receiving packets from them. If in the listening period, it receives a packet, e.g., Q, which is sent to the same direction with P, from one of its neighbors, it ignores the waiting time and determines a new DTP, of course a new waiting time WT' for P and Q. Otherwise, when WT expires and the sensor has not received any packets which are sent to the same direction with P, the sensor appends its residual energy to P and transmits P to its neighbors in the transmission direction of P.

Fig. 5 shows the corresponding state diagram of the EERH, in which events are detected periodically and event packets are transmitted dynamically. In order to have uniform periods among sensors, we should synchronize the sensors in this environment by sending a synchronous signal periodically. The sensors in the center area of this environment, e.g., those surrounded by the red dotted line in Fig. 1, take turns for sending the synchronous signal.

1) EVENTS DETECTED IN DETECTION PERIOD

An event packet carries event information, including event location, constrained time point (CTP) and type of this event, with which system administrator can realize where the event is, and what has happened. CTP is an abstract time point, before which the corresponding event packet should arrive at its sink. Assume that there is an event e_h which is sensed by s_j and the corresponding event packet $P_{h,i}$ is sent to sink k_i. Let $CTP_{h,,i}$ be event e_h's CTP. Therefore $P_{h,i}$ should arrive at k_i before $CTP_{h,,i}$.

$$CTP_{h,i} = DC_h + DTP_{h,j} + \varepsilon \tag{6}$$

where $DTP_{h,j}$ is an absolute time point when e_h is detected by s_j, ε is the error parameter of the monitoring system showing the synchronous difference between s_j and k_i, and DC_h as the delay constraint assigned to event type e_h beforehand is defined as the maximum endurable packet delivering time duration from the time point when s_j detects e_h to the time point when $P_{h,i}$ arrives at k_i.

When detecting the occurrence of an event, sensor s_j, before sending the corresponding event packet $P_{h,i}$ to its neighbors, needs to determine the waiting time WA_j. The propose is to avoid collision of announcements and to rise the shooting opportunity for the sensor having more energy and shorter distance away from sink k_i.

$$WA_j = \frac{D_{i,j}/D}{E_j} \times PD_r \tag{7}$$

where D is the diameter (i.e., the longest geographical distance along the routing path between two arbitrary sensors) of the environment, $D_{i,j}$ is also the geographical distance along the routing path between s_j and k_i, E_j represents the residual energy of s_j and PD_r is the residual time in present detection period. Sensor s_j appends the value of E_j to $P_{h,i}$ before it delivers $P_{h,i}$. In this study, a sensor with a shorter distance away from the sink is given a higher priority to shorten the time required to deliver an event packet. In other words, in (7), the shorter the distance $D_{i,j}$, the shorter the waiting time WA_j. Further, the larger the E_j, the shorter WA_j because the sensor having more energy can relay many more packets. The purpose is balancing the energies among sensors in this environment, thus prolonging the lifetime of this heterogeneous WSN.

The waiting time is also proportional to the residual time of current detection period PD_r. The reason is that we wish the event announcement to be forwarded by the underlying sensor in this detection period. It is also the semantics of (7). However, when the residual time is quite short, the event announcement may fail due to packet collision with other packets transmitted by neighbor sensors, meaning they are mutually in each other's hot regions. The sensor s_j infers packet collision if it does not receive this event packet relayed by one of its neighbors in the next listening period. In this case, s_j will announce this event again in next detection period.

Moreover, to avoid the occurrence of packet storm, after receiving P, if s_j receives P again before it forwards the first receiving P to k_i, then s_j abandons this announcement since one of its neighbor, e.g., s_m's waiting time before forwarding P is shorter than the waiting time that s_j calculates. Abandoning the announcement of this event by s_j can prevent P from being redundantly transmitted among these neighboring sensors, i.e., the event packet P will be forwarded by s_m, instead of by s_j.

2) RELAYING PACKET IN LISTENING PERIOD

In a listening period, on receiving an event packet P, s_j will relay P to one of its neighbors which is on the route toward the corresponding sink, e.g., k_i, but not immediately since s_j's surrounding sensors belonging to underlying WSN or other WSNs may be also relaying an event announcement packet, denoted by Q, Q $\neq$ P, toward the same direction with P. It is better for s_j to aggregate P and Q as one which is then forwarded, consequently saving some amount of energy when delivering P and Q together. Therefore, P's WT before it is delivered, denoted by WR_j, by s_j is calculated as

$$WR_j = \frac{\min(D_{i,j})/D}{(E_j + \gamma ER_j) \times C_j \times R_j} \times PR/w, \quad \forall 1 \leq i \leq n \tag{8}$$

where D as mentioned above is the diameter of the working environment, $D_{i,j}$ is the distance between s_j and k_i, E_j (ER_j) is the residual energy of s_j (s_j's all neighbors in s_j's hot region), γ as the level of neighbors' importance is determined by the underlying monitoring system, C_j is current number of packets that will be aggregated by s_j, R_j represents the number of time slots/rounds that the earliest packet has waited to be aggregated by s_j and PR is the residual time in present listening period.

Let $XT_{i,j}$ be the expected relaying time of an event packet sent by s_j to sink k_i.

$$XT_{i,j} = D_{i,j}/2r \tag{9}$$

where 2r is the minimal transmission range of a sensor in the environment, as mentioned in the description of Fig. 3. In other words, the value of $XT_{i,j}$ is also the maximum number of relaying steps (i.e., number of hops) through the shortest path between s_j and k_i. Let t and Z be current time and size limit of a packet. Let size(P) be the size of an aggregate packet P. Among all events aggregated in P, the CTP of P follows the CTP of the packet with the nearest CTP, e.g., event packet $P_{l,i}$ where

$CTP_{l,i} = \min\{CTP_{h,i} |\ CTP_{h,i}$ is the CTP of event packet $P_{h,i}$ and $P_{h,i}$ is one of the packets aggregated in P transmitted toward the direction of sink $k_i\}$

and if the $CTP_{l,j}$ satisfied

$$CTP_{l,i} \leq 2XT_{i,j} + t \tag{10}$$

then P's w in (8) is 2; else if the size(P) satisfied

$$\text{size(P)} \leq 0.5 \times Z, \quad \text{for } Z \geq 4\text{K} \tag{11}$$

meaning that P can still aggregate many more event packets, then P's w in (8) is 0.5 to prolong the WR_j; in all remaining cases, P's w is 1. An aggregate packet Q with $w = 2$ has higher delivery priority than that with $w = 1$, aiming at shortening the waiting time of Q to avoid the embarrassment of Q' CTP. Note that, if P is not the packet sent to sink k_i, $D_{i,j} = \infty$. When both E_j and ER_j are higher, the WR_j is shorter. Since s_j and its neighbors possess more energy, they are able to relay many more packets. It is also one of the methods to balance the energy among sensors. Further, the larger the C_j and the larger the R_j, the shorter the WR_j since the former (i.e., about C_j) is to avoid aggregating too many packets. The probability that a long packet collides with other packets is high. The latter (i.e., about R_j) is to prevent a packet from being stuck by s_j for a long time.

When the waiting time is up and s_j does not receive any related packets, it aggregates all packets, that have ever received and need to deliver toward the same direction, as one and then forwards the aggregated packet to its neighbors. To avoid redundant transmissions, when s_j receives one that exists in its relaying list, it drops this packet. If the waiting packet includes more than one event packet, the newly arriving packets then wait for next listening period and may aggregate again. The aggregation can reduce the size of transmitted data, denoted by p_{out}, as

$$p_{out} = (1 - \delta) \times \sum_{i=1}^{v} p_i, \quad v > 1 \tag{12}$$

where p_i is the size of the ith aggregated packet; v is the total number of aggregated packets; δ is the aggregation factor, $0 \leq \delta \leq 1$. Because the size of an aggregate packet is smaller than the total size of all aggregated packets, the energy consumed is lower.

In order to improve the calculation accuracy of waiting time, when a sensor receives packets from neighbors, it updates its records of the receiving packets and the residual energy of neighbors so as to maintain the statuses of these neighbors.

IV. EVALUATION AND DISCUSSIONS

This section evaluates the EERH and two heterogeneous schemes named DEEC [12] and M-LEACH [10]. M-LEACH as a cluster-based system has two versions, i.e., the M1-LEACH and M2-LEACH. The difference between them is head-election policies. The frequency of cluster head election in M2-LEACH is higher than that in M1-LEACH. The DEEC is also a cluster-based mechanism, in which sensors take turns to be the cluster heads. Both the DEEC and M-LEACH elect cluster heads according to the residual energy of sensors. In addition, these head sensors transmit packets to other clusters with a higher level of amplified energy. Fig. 6 shows the routing examples at some snapshots of the working environment shown in Fig. 1. A star mark surrounded by a colored circle represents the occurrence of an event; a triangle mark surrounded by bold green circle indicates that an event packet has been sent to the corresponding sink.

Moreover, adjacent circles of the same color form the route, through which an event packet is forwarded to its sink. Among these routes, the ones with red circles represent that the transmitted packet along the route is an aggregated one. The delay constraints assigned to different types of events are set to 5 (event with color cyan, i.e. $DC_1 = 5$ in (6)), 8 (event with color blue, $DC_2 = 8$) and 10 (event with color pink, $DC_3 = 10$) rounds. In addition, we set the error parameter ε in (6) to 1 round, and the level of neighbors' importance γ in (8) to 0.5. When the time point, at which a sink is informed of an event, is later than its time constraint, we regard this case an inefficient notification. In these simulations, the time duration of a round is set to 2 seconds. The minimal size of an event packet is 1Kbits. When a packet is longer than 1Kbits, it is an aggregate packet which arggregates more than one event packet.

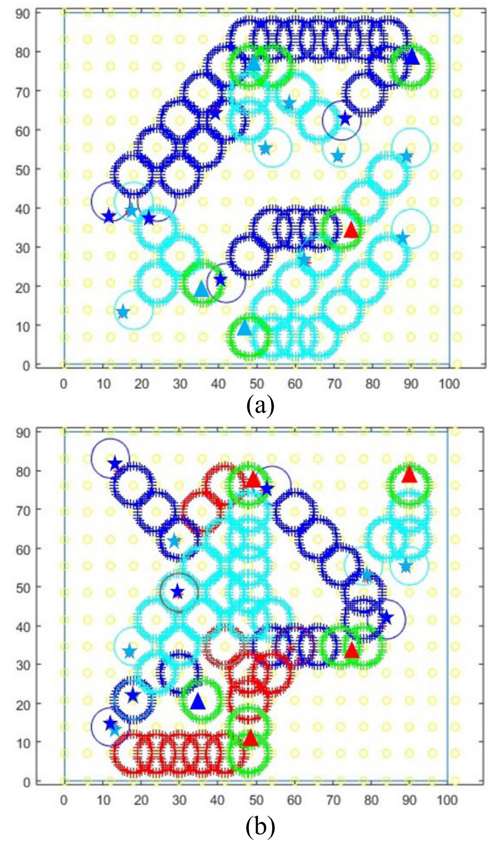

FIGURE 6. The snapshots of event announcements. (a) The adjacent circles of the same color form a route, through which an event packet is forwarded to its sink; (b) the routes with red circles are the paths transmitting aggregate packets.

We evaluate the energy consumption and the lifetime of these test schemes. The heterogeneous sensors in the DEEC, M1-LEACH and M2-LEACH are those with different energy capacities, while in the EERH, heterogeneous sensors represent the sensors with different sensing capabilities. For fair comparison, the total amount of initial energy given to all sensors in these tested schemes are the same. The number and locations of sinks (sensors) deployed are also individually the same. In addition, there are more than two types of events in each time of simulation. Different types of sensors are regularly deployed as a grid (please refer to Figs. 1 and 4).

The parameters in the underlying simulation are listed in Table 1. Sensors know the geographical transmission distance of an event packet. The amount of amplified energy is determined by the distance between transmitter and receiver. For instance, when transmission range is 10m, the amplifier of a sensor consumes energy 10nJ $\times$ 2000 $\times$ 10^2 to transmit a packet of size 2Kbits. The aggregation factor δ is set to 0.3. The simulation results on energy consumption are shown in Fig. 7 when event occurrence ratio is 20% and packet size is 2Kbits. For the cluster-based schemes, the steps of packet transmission can be reduced [25]. Also, when the transmission distance is longer, the cluster heads, which are long, consume much more energy than that required by delivering the head of an aggregate packet of the EERH. Moreover,

TABLE 1. Simulation parameters.

Parameter	Value
Size of network field	100 m x 100 m
Number of deployed sensors	250 - 500
Packet size	1K-10K bits/pkt
Initial energy for each sensor	500mJ
Energy consumed for election	50nJ /bit
Energy consumed for packet transmission or receiving	50nJ /bit
Energy consumed for packet aggregation/segregation	5nJ /bit/signal
Energy consumed by the amplifier	10nJ /bit/m^2
Event occurrence ratio	10% - 40%
Aggregation factor, δ	0.3

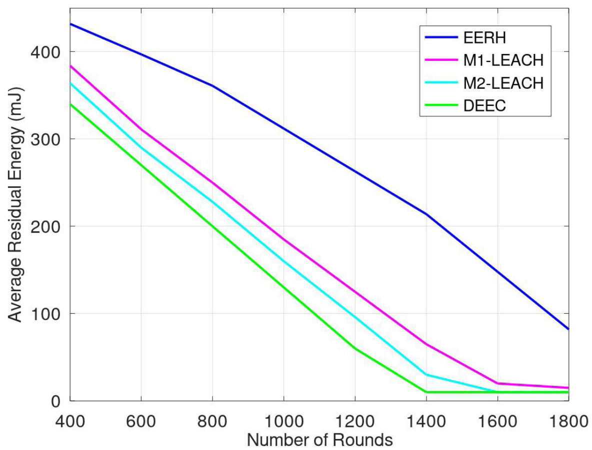

FIGURE 7. The energy consumed by sensors on different schemes when event occurrence ratio is 20% and size of an event packet is 2Kbits.

the cluster-based schemes consume more energy for status exchange and head election. There are the reasons why the EERH outperforms the other schemes. It is clear that the policy of head election influences the energy consumption, particularly when the number of rounds is high. In long-term consideration, the EERH is better than the others.

Fig. 8 shows the number of event packets successfully arriving at their sinks when event occurrence ratio is 30% and size of an event packet is 4Kbits. The y-axis, denoted by ''Average number of notified events'', only counts the events which are notified before their CTPs expire. The dotted lines are the numbers of missed events of different types when employing the EERH where a missed event may be a unnotified one or an inefficient notification (i.e., arrival at its sink but later than its CTP.) Due to generating the same amount of events, the missed events of DEEC and M-LEACH can be calculated. But we did show them for simplifying the figure. When the number of rounds is less than 1000, the performance of these tested schemes are almost the same. Their successful event notification ratios are higher than 99%. When the number of rounds is over 1000, the performance

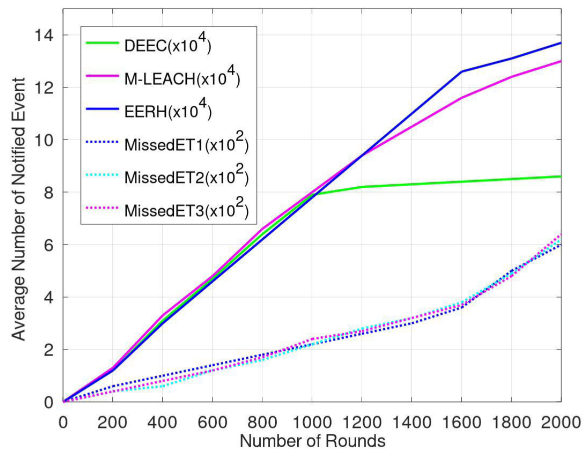

FIGURE 8. The monitoring performance of the test schemes. Some events may be undetected, be detected but event packets do not arrive at their sinks or late arrival of event packets when event occurrence ratio is 30% and size of an event packet is 4Kbits. The three dotted lines plot the missed packets of the EERH only. Note that the total numbers of produced events of the three schemes are the same.

of DEEC is far less than that of the other two because some sensors have exhausted their energy, thus unable to detect events and relay packets. When the number of rounds is higher than 1300, the number of arrival events of M-LEACH is less than that of the EERH. The reason is the same.

Since the simulator produces event types and their locations at random, the numbers of different event occurrences are similar. Following (8), WR_i is type independent, i.e., the numbers of missed notifications for two arbitrary event types are similar. Based on the objective of these schemes, shown in (5), if we limit the ratio of missed events to the value which is less than 1%, the life time of DEEC and M-LEACH end when the numbers of rounds are higher than 1000. For example, the ratios of the DEEC at 1200 and 1400 are 13.5% (=128/948) and 25.1% (=278/1109), respectively, and those of the M-LEACH at 1600 and 1800 are 5.3% (=59/1109) and 8.7% (=111/1271), respectively. Note that the total numbers of events produced for the three test schemes on the same number of rounds (i.e., x-axis) are the same. Of course, due to the time that the experiments last, events produced on different numbers of rounds vary. The higher the numbers of rounds, the more the produced events. Fig. 8 shows that when the number of rounds reaches 1600, the total quantities of missed events and notified events are around 11.1×10^2 and 12.6×10^4, respectively. The ratio of missed events is still less than 1%, and the monitoring still works. The key reasons are that the EERH prevents event packets from long distant transmission and adopts shorter time-constraint first policy.

Moreover, in the following experiment, sensors are deployed randomly, instead of regularly as a grid, in the working environment. Because of random deployment, we double the number of sensors to avoid the case in which some of them are isolated from others, i.e., they are mutually reachable. Randomly deploying sensors incurs some challenges because the number of packets transmitted along a routing path

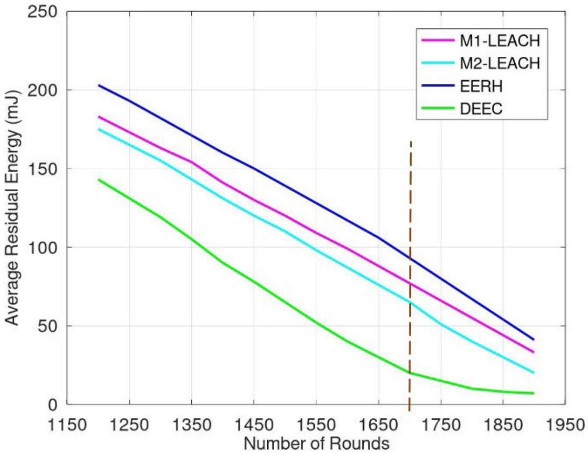

FIGURE 9. The energy consumed by sensors when we double the number of sensors and sensors are randomly deployed.

increases, thus consuming more energy for packet transmission and receiving. The probable reason is that the numbers of sensors in the hot-region for some events are relatively less, thus causing higher probability of duplicated transmissions for these event packets. Fig. 9 shows that when the number of rounds is more than 1200, all the average residual energy are less than the results shown in Fig. 7. Please compare the scales of the y-axes of these two figures. In Fig. 9, the EERH is also better than DEEC and M-LEACHs. Because the EERH cooperates the transmission of event packets in different WSNs and aggregates event packets. Totally, a lower number of packets is sent, thus consuming less energy.

Note that when the number of rounds is over 1700, marked with a dotted line, some routes of the DEEC are unconnected due to out of battery on sensors, resulting in incomplete event notification. Therefore, the curve is relatively gradual. With random deployment and twice amount of sensors, when the number of rounds is over 1680, the curve of the EERH is a little closer to that of the M-LEACH. In fact, a cluster-based scheme exploits those head nodes with higher energy since it is good for transmitting many more packets to a farther sink.

Fig. 10 shows the residual energy of the EERH given different packet sizes which are 1Kbits, 2Kbits, 4Kbits, 6Kbits, 8Kbits and 10Kbits on the ratio of event occurrence which is 20%. Observing a specific number of rounds, for example, 1200, when the size of a packet is larger, the total energy consumption is lower. This is because a larger packet can aggregate many more event packets. As shown in (12), the total size of transmission is reduced, thus lowering the energy consumed for packet transmission. Nevertheless, following (10), if an aggregate packet P with the CTP – t is less than two times of expected relaying time where t is current time, even the size of P is not achieved the limit size, it will be forwarded to its neighbors. Fig. 10 shows that when the size of a packet is up to 10K, the performance does not improve. The probable reasons are that lots of packets are sent out before their sizes reach 10K, and a longer packet lengthens the packet's transmission time. The probability that this packet is dropped and collided with other packets is then higher.

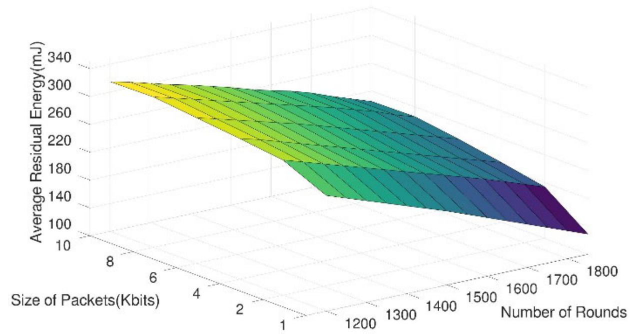

FIGURE 10. The energy consumed by sensors of the EERH on different sizes of packets and different numbers of rounds when event occurrence ratio is 20%.

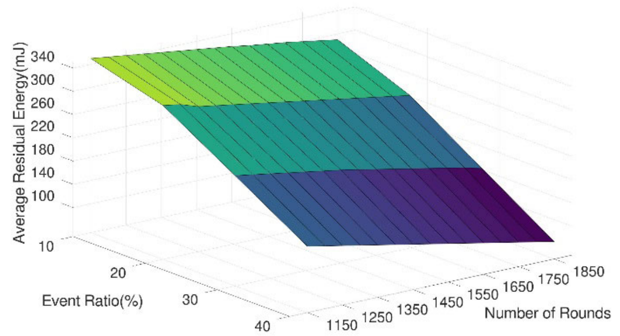

FIGURE 11. The energy consumed by sensors on different event occurrence ratios and different numbers of rounds when the EERH is employed.

Basically, it is possible that a packet with 2Kbits as its maximal size may not aggregate information in it, i.e., it only contains data of one event. But a packet with 1Kbits of maximal size must carry event data in it, but no aggregation is possible since the size of an event packet generated by a sensor is 1Kbits. As shown in Fig. 10, the energy consumed by 1Kbits packets is much more than that consumed by packets of 2Kbits or a larger packet size. The EERH aggregates packets when these packets are sent to the same direction, even though the aggregate packet contains data bound for different sinks. Thus the aggregate packet will be segregated into two or more packets somewhere along current routing path. When the ratio of event occurrence is less, the aggregation approach still accelerates event notification and reduces the energy consumption. If the ratio of event occurrence is higher, the aggregated data sent to the same sink may be more efficient.

Fig. 11 shows the simulation results of the EERH on different event occurrence ratios which are 10%, 20%, 30% and 40%. The packet size is 2Kbits. When the occurrence ratio is risen from 10% to 20%, the increase of energy consumption is significant. As the ratio is higher than 20%, the energy consumption rises more sharply.

The propagation time of a packet is the time in which the packet travels along the path PATH(j, i) $=\{s_1, s_2, \ldots, s_{n-1}, s_n\}$ from its source node s_1 to the sink k_i ($= s_n$), including WA_1, $\sum_{i=1}^{n} W\mathrm{R}_i$ and $\sum_{i=1}^{n} tt_i$ where n is the number of

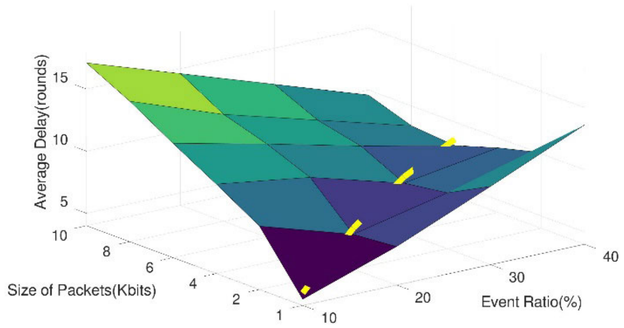

FIGURE 12. The transmission delays of event packets by using the EERH on different ratios of event occurrence and different maximal sizes of packets.

transmission along the path from s_j to k_i, and WA_i and WR_i are defined in (7) and (8), respectively. The tt_h is transmission time from s_h to s_{h+1}, $1 \leq h \leq n-1$. Note that the propagation time must be shorter than this event type's delay constraint (please refer to (6)). Otherwise, it is an inefficient notification. In the following, we evaluate the average propagation time of events during 1000 rounds given different maximal packet sizes which are 1Kbits, 2Kbits, 4Kbits, 6Kbits, 8Kbits and 10Kbits and different ratios of event occurrence which are 10%, 20%, 30% and 40%. In order to have the propagation time of events unrestricted by their time constraints, all events are generated with a large time constraint. Thus, when deriving the waiting time of packets relaying, the value of w in (8) is always equal to 1 since (10) will not be satisfied. Fig. 12 shows the results. When packet size is 1Kbits, the propagation time is longer on higher event occurrence ratios because more events generate more packets.

Nevertheless, when the maximal packet size is longer than 1Kbits, the shortest propagation time in average is not on 10% of event occurrence ratio, e.g., those for 2Kbits and 4Kbits are on 20% and 40% of event occurrence ratios, respectively. As the maximal packet size is higher than 6Kbits, because the number of aggregated packets may achieve the maximum no sooner after this sensor possesses the first aggregated packet, the average propagation time on higher ratios of event occurrence are relatively shorter. For example, when packet size is 6Kbits, the average propagation time on event ratios from 10% to 40% is reduced from 13.2 to 8.1 rounds. Other packet sizes have similar situation, except the case when packet size is 1Kbits. Now we can conclude that, when the event ratios are higher, a larger packet size is recommended.

In Fig. 12, the yellow dashed line shows the best cases on different packet sizes and different event occurrence ratios. For instance, when the ratio of event occurrence is 20% (40%), the shortest average propagation time is the case when the size of packet is 2Kbits (4Kbits).

Therefore, when the propagation time of events is constrained to less than 10 rounds, 1Kbits (2Kbits) packet size is chosen if the event occurrence ratio is around 10% (20%). If the delay constraint is limited to less than 15 rounds, 6Kbits

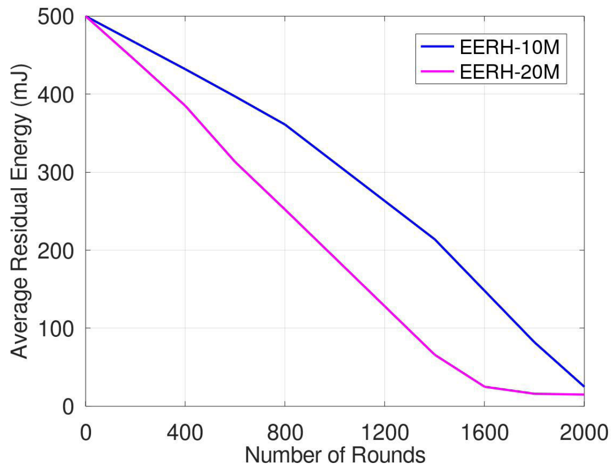

FIGURE 13. The energy consumed by sensors by using the EERH on different transmission distances (i.e., 10m and 20m) and different numbers of rounds.

packet size will consume less energy than that consumed by 1 or 2 Kbits packets.

Recall, Fig. 4 shows the hot region and sub-hot region for event transmissions. When the transmission range, i.e., the longest transmission distance, of a sensor is 10m and sensor s_j delivers an event packet P toward P's sink, the neighboring sensors in s_j's hot region will receive P simultaneously. Thus, the duplicate transmissions of P would not occur among these neighbor sensors. However, the sensors located in sub-hot region may not receive P because the distance between s_j and each of them is longer than 10m. Hence, duplicate transmissions may occur for some events when the energy of sensors in the hot region is less than that of sensors in the sub-hot region.

Fig. 13 illustrates the experimental results of energy consumption for the EERH on different transmission ranges which are 10m and 20m. The line denoted by EERH-10M represents 10m transmission range. In the first 800 rounds, the energy difference between two arbitrary sensors is insignificant. Of course, sensor s_j in the hot region should be on one of the shorter paths between events and sinks. Hence the energy consumption for delivering P will be much less. In addition, after 800 rounds, the energy consumption is higher (the curve decreases more sharply) due to duplicate transmissions of P by sensors in the sub-hot region. Moreover, after 1300 rounds, the duplicate transmissions are further serious.

On the other hand, when the transmission distance of a sensor is 20m, both the neighbors in hot region of the event and those in the sub-hot region will receive P. Also, the energy consumption is proportional to d^2 where d is the distance between the sender and receiver, meaning the energy consumed by EERH-20M for transmitting P is 4 times that required by EERH-10M. As illustrated in Fig. 13, when the number of rounds is above 1600, the lifetime of the monitoring environment end because lots of sensors have exhausted their energy. Even though the energy decreasing speed, i.e., slope of the curve, of EERH-10M above 1300 rounds is faster than that of EERH-20M below 1600 rounds, the EERH-20M does not outperform the EERH-10M. The key reasons are energy consumption for transmitting a packet P and duplicate transmission of P.

The simulation results demonstrate that aggregating event packets in a heterogeneous sensor network can reduce energy consumption for packet delivery. Without exchanging sensor statuses and electing cluster head, exploiting aggregation appropriately can help to extend the lifetime of sensors so as to monitor the underlying environment much longer. Moreover, when using the EERH, we can choose the appropriate size of event packets and transmission range of a sensor or adjust the aggregation parameters, including the ratio of event occurrence and delay constraints of different event notifications, attempting to prolong the life time of WSNs.

V. CONCLUSIONS AND FUTURE STUDIES

In this study, we propose a dynamic routing scheme, i.e., the EERH, in heterogeneous WSNs. Different types of events are detected by different types of sensors and event packets sent to the same direction are aggregated before transmitting these packets to their sinks. Along the transmission paths, sensors of type A can relay packets of type B. When receiving a packet, e.g., P, a sensor, e.g., s_j's neighbors help to transmit P. This may save energy in transmitting P to its sink since for a specific WSN, the number of sensors that can relay packets for its events increases. As we know, energy consumption E for packet delivery is proportional to d^2 where d is the distance of wireless transmission. According to our simulations, the EERH prolongs the lifetime of sensors and makes more flexible relaying chances in a heterogeneous WSN. Therefore, it efficiently elaborates the sensors in the environment for detecting and transmitting events, thus effectively lengthening the monitoring lifetime of networks. Moreover, when using the EERH, we can adjust its parameters to satisfy the requirements of the monitoring environment, for instance, the ratio of event occurrence, and delay constraints of events.

In the future, the security of the EERH will be explored, like those in [26], [27]. We would also like to derive the behavior and reliability models for the proposed system so that users can comprehend the behaviors and reliability before using it. These constitute our future studies.

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